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RECOMBINANT β_2-ADRENERGIC RECEPTOR DELIVERY AND USE IN TREATING AIRWAY AND VASCULAR DISEASES

BACKGROUND OF THE INVENTION

This application claims priority to U.S. Provisional Patent Application, 60/182,502 filed on February 15, 2000, which is herein incorporated in its entirety by reference.

The present invention relates to a novel treatment of airway and vascular diseases in which dilation of the affected airway or blood vessel would be of benefit to relieve symptoms, in diseases, such as asthma, pulmonary hypertension and systemic hypertension. The present invention provides a method for increasing the β_2-adrenergic receptors (β_2AR) in the airway epithelial cells and smooth muscle cells and blood vessel endothelial cells and smooth muscle cells resulting in the dilation of the airways and blood vessels, thus relieving symptoms of airway and vascular diseases. The present invention particularly relates to a novel adjunctive treatment of airway and vascular diseases by delivering a first composition comprising a recombinant vector that carries the nucleic acid sequence encoding the native β_2AR or a modified β_2AR, that is delivered into the airways and blood vessels, allowing infection or transduction of at least one type of cell selected from epithelial cells lining the airways, endothelial cells lining the blood vessels and from smooth muscle cells composing the airways and blood vessels.

The present invention more particularly relates to a novel adjunctive treatment of severe asthma in patients who have become hypo-responsive to the bronchodilatory effect of β_2-adrenergic agonists (β_2-agonists) or who may benefit from increasing the bronchodilatory effect of β_2-agonists. The present invention employs a recombinant vector that carries the nucleic acid sequence encoding the native β_2AR or a modification thereof, that is delivered into the airways via bronchoscopy, allowing infection or transduction of at least one type of cell from the epithelial cells lining the airways and from the smooth muscle cells composing the airways and expression of the β_2ARs in these cells. The present invention relates to the delivery of the recombinant vector simultaneously or

sequentially with β_2-agonists that are administered to treat acute symptoms by producing rapid bronchodilation.

The present method relates to an *in vitro* method of expressing the β_2AR gene and evaluating the effect of pharmacological compositions on the expression of β_2ARs in mammalian cells that are transduced with a recombinant vector that carries the nucleic acid sequence encoding the native β_2AR or a modified β_2AR.

Asthma is a collection of symptoms that produces an airway state that causes excessive airway narrowing in response to stimuli that typically do not produce the same effect on the nonasthmatic airway.[151] In the past, asthma's etiology was ascribed principally to airway smooth muscle spasm and bronchodilator therapy was the front-line approach for managing asthmatic patients. It is now evident that asthma is a disease of chronic inflammation involving inflammatory cells that release numerous mediators. These mediators initiate airway hyperresponsiveness to various stimuli and lead to the clinical endpoint of bronchoconstriction.[6] The majority of asthmatic patients display bronchospasm, airway inflammation and mucous plugging. Asthmatics experience recurrent episodes of wheezing, chest tightness, and coughing, particularly at night and in the early morning. In the United States, asthma affects 14 to 15 million individuals and causes more than 5,000 deaths annually. Two general classes of medication are currently available for treatment: long-term control medications (e.g., corticosteroids, cromolyn sodium, methylxanthines, leukotriene modifiers) aimed at obtaining control of the persistent, inflammatory component of asthma and quick relief medications (e.g., short-acting β_2-agonists, anti-cholinergics) used to treat acute symptoms, such as wheezing and shortness of breath.

In the mature airway, the epithelium forms a continuous lining whose cellular composition varies with anatomical location.[14,112] From these studies, at least 12 types of airway epithelial cells have been identified, although the proportions of the various cell types vary from species to species.[14,112] Within the proximal airway, the epithelial cell layer is thicker and assumes a pseudostratified appearance.[14] Basal, ciliated, intermediate, and goblet cells are present in the proximal airway and typically there is an absence of Clara cells. In the distal airways, the epithelium becomes thinner. Within the bronchioles, the epithelium is composed of low cuboidal cells and Clara cells become more prevalent. Airway epithelium is generally considered to perform five primary functions:[116] 1) acts as a barrier to the diffusion of particles from the airway to underlying lung structures, 2)

secretes mucin-like materials, 3) clears the airway of debris through ciliary action, 4) repairs damaged tissue following injury in the airway, and 5) modulates the response of other airway cells particularly to environmental agents that enter the airways. Airway epithelial cells regulate bronchoconstriction,[42] bronchial vascular responses,[66] and inflammatory cell recruitment into the airway.[75,118] Because of easy accessibility, airway epithelium is an attractive target for delivering genetic material to treat both acquired and inherited lung diseases. A prominent example involves the cystic fibrosis transmembrane conductance regulator (CFTR) gene, in which mutations cause the disease cystic fibrosis.[1,150]

The bronchodilatory effects of β_2-adrenergic agonists are exerted by stimulating airway smooth muscle relaxation directly and secondarily by causing release of an airway smooth muscle relaxing factor from epithelial cells. Figure 1 provides a diagram of the β_2AR life cycle following agonist binding to the receptor. Despite their widespread use, β_2-agonists have several shortcomings. For maximum symptom control, frequent dosing is required. This can lead to development of subsensitivity or tolerance, which blunts their effectiveness. Development of tolerance to inhaled β_2-agonists is due to either uncoupling of β_2ARs from downstream effector proteins that produce bronchodilation or the actual loss of β_2ARs from the cell surface.

Although beneficial in the short-term, prolonged use or overuse of β_2-agonists has been associated with reduced β_2AR responsiveness. The phenomenon of reduced β_2AR responsiveness, also known as tachyphylaxis or tolerance, results from a culmination of events, which include desensitization, sequestration, and down-regulation. Desensitization occurs as a consequence of receptor phosphorylation by either protein kinase A (PKA) or a G protein coupled receptor kinases (GRK). Phosphorylation of the receptor causes the receptor to uncouple from downstream effector proteins and also promotes binding of high-affinity arresting proteins, known as arrestins. Binding of arrestins to the β_2AR also targets the receptor for sequestration and down-regulation. Sequestration (or internalization) moves the β_2AR from the cell surface to endosomes located in the cell's interior. Since the native hormones/neurotransmitters epinephrine and norepinephrine cannot cross the cell membrane, internalized receptors are no longer able to trigger a physiological response. Once in endosomes, receptors reach a sorting point in the pathway. The degradation pathway results in a net loss of receptors, also called down-regulation. Internalized β_2ARs

can also be recycled back to the cell surface. It is not known what determines whether an internalized β_2AR will be degraded or recycled. Thus, when a severe asthmatic uses his/her β_2-agonist inhaler too many times, levels of β_2ARs decrease in their airways to a point where no matter how much β-agonist they use there are not enough receptors available to bind the drug and produce airway relaxation.

The present invention overcomes this loss of native β_2ARs in asthma patients by the expression of recombinant β_2ARs in airway epithelial and smooth muscle cells to keep β_2AR levels at normal or even at higher than normal levels on the cell surface. A recombinant β_2AR gene, under the control of a very active viral promoter, transcribes high levels of β_2AR mRNA, augmenting the β_2AR mRNA that simultaneously is made by the native β_2AR gene. The mRNA is translated into β_2AR protein and is delivered to the cell membrane at a rate that is faster than the rate at which β_2ARs are removed from the membrane via the desensitization/sequestration/down-regulation pathway.

The β_2AR is a member of a superfamily of membrane assoicated receptors coupled to guanine nucleotide regulatory proteins (G-proteins) and produces its effects by activating intracellular signal transduction pathways.[136] Results from radioligand assays and receptor autoradiography studies have documented the presence of β_2ARs on a variety of cell types within the mammalian lung.[8, 98] Airway epithelial cells in human,[72] murine,[106] bovine,[101] and rat[125] lungs express β_2ARs. Several aspects of airway epithelial function are under the control of β_2ARs. β_2-agonists increase bronchial epithelial chloride and mucus secretion, and increase ciliary activity.[99] The effects of inhaled β_2-agonists on mucociliary clearance in humans seem to be variable. In one study, the β_2-agonist, procaterol, had no effect in both controls and in asthmatic individuals.[68] However, inhaled terbutaline increases mucociliary clearance in both controls and in patients with asthma.[93] Results from several studies have suggested that the relaxation of airway smooth muscle that occurs in response to β_2-agonists is reduced if the bronchial epithelium is removed.[42, 155] This finding could be explained by the release of a smooth muscle relaxing factor from bronchial epithelial cells in response to stimulation with β_2-agonists. This factor, designated epithelium-derived relaxant factor (EpDRF),[42, 155] could either act directly on smooth muscle to cause relaxation or alternatively enhance the effect of β_2-agonists on bronchial smooth muscle (See a schematic of the proposed mechanism in Figure 2).

β_2-agonists and glucocorticoids are the two most effective treatments available for asthma therapy and frequently are used in combination. Glucocorticoids are used principally because of their anti-inflammatory properties,[7] although additional beneficial effects of glucocorticoids in the asthmatic lung have been observed.[135] Synthetic glucocorticoids are efficacious for treating asthma and other diseases with associated inflammatory processes because they mimic glucocorticoids produced endogenously by the adrenal cortex. The cellular and molecular mechanisms of action of the glucocorticoids have been extensively studied.[135, 154] The current model of glucocorticoid action postulates intracellular glucocorticoid receptors, which in the absence of ligand, are complexed with heat shock proteins (hsp90, hsp56, hsp70 and an acidic 23 kD protein) (See Figure 3). Glucocorticoids are found in the blood bound to transcortin, albumin, and other serum proteins. Free glucocorticoids enter target cells, by still unidentified mechanisms[49, 152] and bind to glucocorticoid receptors causing dissociation of the associated heat shock proteins. Association of hsp90 with glucocorticoid receptors appears to maintain the hormone binding domain in its high affinity conformation.[113] The functional roles of the other associated heat shock proteins are not as well understood, but may include trafficking of the receptor within the cell.[113] The glucocorticoid receptor is a member of a superfamily of transcriptional regulators that include receptors for estrogens, progesterones, androgens, vitamin D, thyroid hormones, and retinoic acid.[83] Members of the superfamily share a similar structure with functional domains for binding of hormone, binding to DNA, and transcriptional activation. Hormone-receptor complex translocates from the cytoplasm to the nucleus. Activated glucocorticoid receptor with hormone bound has an increased affinity for binding to specific DNA sites termed glucocorticoid response elements (GRE) found within glucocorticoid reponsive genes. GREs can either be simple or composite.[48] Most simple GREs consist of two half-site hexamers separated by three nucleotides with resemblance to the consensus sequence GTCACAnnnTGTTCT. Association of glucocorticoid receptor, typically as a homodimer, to simple GREs results in enhanced transcription of the target gene. A second type of DNA sequence that binds glucocorticoid receptors, termed composite GREs, has been found in certain glucocorticoid-responsive genes.[31] At composite GREs, the hormone receptor complex interacts with both specific DNA sequences and other transcription factors to regulate transcription.[31, 47, 91] The first demonstrated composite GRE was shown to have binding sites for both the glucocorticoid

receptor and activating protein-1 (AP-l).[31] AP-l is a dimer of the oncogene products *c-fos* and *c-jun*. Since glucocorticoid receptors are expressed in many cell types, composite GREs may explain how signal specificity can be achieved in a system with an apparent common final pathway.[48]

For many G-protein coupled receptors, modulation of receptor number is an established mechanism controlling responsiveness to hormones and neurotransmitters. Heterologous regulation of β_2AR levels by glucocorticoids is a physiologically important example of such control.[23] Numerous *in vitro* and *in vivo* studies in a variety of cell types have shown that β_2AR 1evels and β-agonist-stimulated adenylyl cyclase activity are increased by glucocorticoids.[19,28,46,104,140,157] Glucocorticoids increase β_2AR levels in the lung of several species including rat, rabbit and human.[19, 84,87] The increase in β_2AR number results from an increase in rate of new receptor synthesis,[104] which is preceded by increased steady-state levels of β_2AR mRNA [23, 28,58, 59,81, 90, 140] and increased transcription rate of the β_2AR gene.[23, 59, 81] The increase in β_2AR density induced by glucocorticoids is blocked by the transcriptional inhibitor actinomycin D.[95] Taken together, these findings suggest that enhanced β_2AR gene transcription is a principal mechanism underlying glucocorticoid mediated increases in β_2AR levels. The β_2AR genes from several mammalian species contain GRE-like sequences in both coding and non-coding regions.[16, 39, 70, 73, 88] Although indirect evidence suggests that the 5'-noncoding region of the β_2AR gene is involved,[82] data discussed below identifies specific genetic elements responsible for the functional effect of glucocorticoids on β_2AR gene transcription.

Since the development of β_2-adrenergic selective drugs and metered-dose inhaler delivery systems, agents that target the β_2ARs have become the most commonly prescribed medications for asthma.[34] The principal beneficial effects of β_2-agonists are on bronchomotor tone and airway patency. Agonist stimulation of β_2ARs in airway smooth muscle inhibits contractile processes, resulting in bronchodilation.[115] This is an important property of β_2ARs because several bronchoconstricters (histamine, bradykinin, acetylcholine, LTD_4, and PGD_2) are elevated in the asthmatic lung.[5]

β_2-agonists are effective bronchodilators in large and small airways.[97] β_2AR-mediated processes in airway epithelial cells *(e.g.,* mucous clearance, production of bronchoactive factors) may also either directly or indirectly affect the contractile state of

airway smooth muscle,[92] β_2-agonists have been shown to decrease mediator release from basophils and mast cells.[22,109] Administration of β_2-agonists reduces vascular leakage caused by inflammatory mediators including histamine, platelet activating factor, and certain prostaglandins.[105,111] Finally, β_2ARs are expressed on the surface of potential inflammatory cells, including eosinophils, alveolar macrophages, lymphocytes and polymorphonuclear leukocytes.[24, 33, 78, 156] While the role of the β_2AR on proinflammatory cells in the asthmatic lung is currently unclear, some physiological effects have been reported. β_2-agonist treatment *in vitro* is associated with decreased proliferation of human T lymphocytes in response to mitogenic stimuli[24] and inhibition of lysosomal enzyme release from granulocytes.[65]

Despite their well-documented clinical efficacy, regular use of β_2-agonists and glucocorticoids can lead to several clinical problems. Doubts concerning the safety of β_2-agonists arose from epidemiologic studies conducted in New Zealand[25, 55, 110] and Canada[133] that demonstrated an association between the regular use of β_2-agonists, particularly fenoterol, and the risk of dying from bronchial asthma. The conclusions drawn from these studies are controversial and do not necessarily prove a cause-effect relationship since patients with more severe asthma, and therefore a higher risk of fatal attacks, are more likely to use β_2-agonists more frequently or at higher doses.[5] A balanced review on the safety of β_2-agonists also can be found.[141] Overuse of inhaled β_2-agonists may also increase asthma morbidity. Separate studies have shown that regular β_2-agonist use can be associated with poorer control of symptoms and increased airway hyper-responsiveness compared to asthmatics who use the same medications "as needed".[128, 142] These observations are not surprising since it is well-known that β_2ARs are prone to the process of desensitization and down-regulation resulting in loss of receptor function following prolonged β_2-agonist exposure.[57, 74] The present invention circumvents the adverse effects associated with overuse of β-agonists.

Because all cells express a common glucocorticoid receptor, every cell and organ system can be affected by administration of exogeneous glucocorticoids. Numerous potential adverse effects that can arise from systemic glucocorticoid use,[132] and include effects that can occur immediately *(e.g.,* hypokalemia and hyperglycemia), those that develop over a longer period of time *(e.g.,* osteoporosis and cataracts), and those that are limited to children *(e.g.,* growth suppression). Chronic glucocorticoid use results in

development of posterior subcapsular cataracts with a prevalence of up to 29% in adults and children.[120, 145] Patients on >7.5 mg/day prednisone for longer than 6 months are at risk for developing osteoporosis.[79] Inhibition of linear growth in children has been observed with regular daily therapy, frequent short course therapy and high-dose alternate day therapy with glucocorticoids.[10, 96, 129] Inhaled glucocorticoids, used as long-term management by many asthmatics, generally display fewer risks than oral glucocortoids.[53] At doses up to 800 μg/day, few clinically important adverse effects are observed with oral glucocorticoids; however, with long-term use of doses greater than 800 μg/day, osteoporosis, suppressed linear growth in children, adrenal-pituitary axis suppression, and cataracts are the most likely adverse effects to develop.[15, 53, 143] Although inhaled corticosteroids have significantly less potential for causing adverse effects compared to oral systemic corticosteroids, current recommendations are to use the lowest possible dose to maintain control of symptoms.[40] Some of the beneficial effects of glucocorticoids are the result of increased β_2AR numbers. The present invention provides a method whereby β_2AR overexpression in airway epithelial cells and smooth muscle cells leads to decreased glucocorticoid requirements in severe asthmatics.

Shortcomings in safety and persistently delivering effective quantities of specific proteins to patients using recombinantly produced proteins has led to the development of gene therapy methods for delivering sustained levels of specific proteins into patients. Gene therapy is defined as the insertion into a patient of DNA that codes for either normal or altered genes,in order to correct a genetic or acquired disorder. The normal or altered gene that is inserted corrects the disorder via production in the patient of either missing, defective, or insufficient gene products. The DNA may be introduced by known cell transfection methods, but viral-mediated gene delivery methods, such as retrovirus, adenovirus, herpes virus, pox virus, and adeno-associated virus (AAV) are used in more than 95% of gene therapy trials conducted.[159]

Gene therapy techniques utilize various vehicles for gene transfer and Table 1 of Kay et al.[160] disclose retroviruses, adenoviruses and AAV as viral vehicles and liposomes as nonviral vehicles. Each one of these vehicles has limitations in gene therapy applications (discussed in Stone et al.[161]). Nonviral vechicles, such as liposomes presently lack target cell specificity. Widespread expression of transgenes can have deleterious outcomes. The disadvantages of retroviral vectors include random insertion into the host genome,

inactivation by human complement, inability to transduce non-dividing cells, and possible decreased transgene expression over time. Additionally and very importantly, the retroviruses and retroviral vectors have been banned for use in gene therapy by the Food and Drug Administration. The principal drawback of adenoviruses is a significant host immune response against the viral vector, vector-encoding proteins, and the cells expressing these proteins. This leads to inflammation and elimination of transduced cells by the immune system, requiring frequent re-administration of the transgene. Because adenovirus does not incorporate into the host genome, duration of transgene expression is limited. AAV possesses a number of features not possessed by the other viruses, such as: wide host range, ability to infect different species, no known association with any human or animal disease; does not appear to alter the biological properties of the host cell when it integrates, its stability over a wide range of physical and chemical conditions, its small size, and less complicated epitopes presented to a patient than adenoviruses. For all of these reasons, a more suitable choice of a vector for transducing epithelial cells, is the AAV vector as originally suggested by Hermonat et al.[62]

The AAV genome is a linear, single-stranded DNA molecule containing 4681 nucleotide and an internal non-repeating genome flanked on each end by inverted terminal repeats (ITRs). The ITRs are approximately 145 base pairs in length and have multiple functions. The internal non-repeated portion of the genome includes two large open reading frames, known as the AAV replication (rep) and capsid (cap) genes, code for viral proteins that allow the virus to replicate and package the viral genome into a virion.

AAV is a helper-dependent virus that requires co-infections with a helper virus, such as adenovirus, herpesvirus or vaccinia) in order to form AAV virions. AAV has been engineered to contain heterologous genes by deleting the internal non-repeating portion of the AAV genome (i.e., the rep and cap genes) and inserting the heterologous gene linked to a promoter between the ITRs. The ITRs are the only viral elements necessary for efficient encapsidation and integration of the viral genome of the host cell.[162] The AAV genome stably integrates into a specific site in human chromosome 19[163] and AAV is able to transduce both mitotic and post-mitotic cells.[164] In order to prepare AAV a helper virus (usually adenovirus) is required. Although high titer AAV preparations result, the preparations are contaminated with helper virus that must be removed by tedious purification steps. Alternative strategies to prepare recombinant AAV have been

developed[165] (See also U.S. 6,004,797, U.S. 6,001,650, U.S. 5,945,335) that produce high AAV titers with no helper virus contamination.

In regard to the usefulness of gene therapy methods for the treatment of asthma, a number of research groups have looked at new treatments for asthma. Demoly et al. (1997) [166] considered the possibility of a gene therapy based strategy for the treatment of asthma. This publication admits that in the treatment of asthma, there are no deficient genes to replace and no protein is truly repressed but rather there is a hypersecretion. These authors consider blocking the expression of an inflammatory or immunoregulatory protein but admit that sophisticated gene therapy techniques would be required. Further, a publication by Rogers *et al.* (1998)[167], considers gene therapy as a new approach to treat lung disease because the lung provides an accessible target through the airways or the vasculature. This publication considers the lung diseases of α_1-antitrypsin deficiency and cystic fibrosis as good candidates for gene therapy because the genetic defect in each disease is well characterized. This publication also considers the different vectors and the advantages and disadvantages of using them.

McGraw *et al.* reported at the 1998 ALA/ATS International Conference[89] and in a later publication[168] that their group had generated transgenic mice lines using the human surfactant protein C promoter and the rat CC10 promoter to overexpress the human β_2AR in distal alveolar epithelium (type II cells) and bronchial tracheal epithelium (Clara cells). Epithelial cell β_2AR overexpression was verified by receptor autoradiography. These transgenic mice lines may be useful in selectively isolating the effect of proximal and distal epithelial cell β_2ARs upon airway physiology and pathophysiology. In 1999, McGraw *et al.*[169] reported that transgenic mice expressed β_2ARs in airway smooth muscle using a mouse smooth muscle α-actin promoter as compared to normal mice.

Another group looked at the overexpression of β_2AR in adenoviral transduced cultured adult rabbit ventricular myocytes,[170] and concluded that recombinant adenoviral gene transfer of β_2AR or an inhibitor of β-adrenergic receptor kinase (βARK)-mediated desensitization can potentiate β-adrenergic signaling. Recently another publication by some of the members of the previous group, delivered adenoviral transgenes including the human β_2AR gene to the myocardium of rabbits using catheter-mediated delivery. This study demonstrated global myocardial *in vivo* gene delivery and that genetic manipulation of β_2AR density can result in enhanced cardiac performance as compared to control rabbits.

The human β_2AR gene is known and sequenced. The first report of cloning and sequencing the human β_2-AR was reported in.[171, 73]

As discussed above, a significant problem associated with prolonged treatment of asthmatics with β_2-agonist treatment is desensitization or tolerance. The loss of clinical responsiveness to β_2-agonists has potentially serious outcomes including increased mortality, poor baseline asthma control, escalating medication usage, and increased cost of care. The present invention provides a recombinant vector and a method of using this vector to provide additional β_2ARs to airway epithelial cells and smooth muscle cells, but particularly airway epithelial cells, to provide increased levels of β_2ARs in these cells. The increased levels of β_2ARs alone or with adjunct β_2-agonists or controlled β_2AR expression by endogenous or administered inducers of the promoter operably linked to the β_2AR gene provide a method of treating airway diseases, such as asthma. The present method also is useful for providing treatment for other diseases that can benefit from increased levels of β_2ARs, such as vascular diseases.

SUMMARY OF THE INVENTION

The present invention relates to vectors comprising a DNA sequence encoding a β_2AR operably linked to a promoter that is functional in at least one cell type of the airways and blood vessels of a human subject. In a preferred embodiment, the vectors are adeno-associated virus based. Adeno-associated virus has a natural tropism for airway epithelia. So these adeno-associated virus based vectors are particularly preferred for respiratory gene therapy applications. The present invention is directed to cells containing the vector.

The present invention is further directed to a method for providing a β_2AR to airway epithelial cells, airway smooth muscle cells, blood vessel endothelial cells, blood vessel smooth muscle cells or a combination thereof, of a human subject comprising administering to at least one of these enumerated cell types, a first composition comprising a vector comprising a DNA sequence encoding a β_2AR operably linked to a promoter that is functional in at least one of the cells, under conditions whereby the DNA sequence encoding said β_2AR is expressed in at least one of these cells. In a further embodiment, the DNA sequence encodes a β_2AR that is modified in its function as compared to the native β_2AR.

The present invention further is directed to an adjunct therapy for treating a human subject having airway or vascular disease comprising administering to at least one cell type selected from the group consisting of airway epithelial cells, airway smooth muscle cells, blood vessel endothelial cells, and blood vessel smooth muscle cells of the human subject, a first composition comprising a vector comprising a DNA sequence encoding a β_2AR operably linked to a promoter that is functional in at least one of these types of cells of the subject, under conditions whereby the DNA sequence encoding the β_2AR is expressed in at least one of these types of cells; and administering a second composition comprising at least one β_2-agonist to at least one cell type of the subject.

The present invention additionally is directed to administering simultaneously or after the administeration of a vector comprising a DNA sequence encoding a β_2AR operably linked to a promoter that is functional in at least one of the types of cells of the subject enumberated above, a hormone or other pharmacological agent that induces the promoter to express β_2ARs.

The present invention is further directed to pharmaceutical compositions containing the vector comprising a DNA sequence encoding a β_2AR operably linked to a promoter that is functional in cells of the airway epithelium and smooth muscle cells and blood vessel endothelium and smooth muscles.

The present invention additionally is directed to a kit that contains in separate containers at least one pharmaceutical composition comprising the vector comprising a DNA sequence encoding a β_2AR operably linked to a promoter that is functional in cells of the airway epithelium and smooth muscles and blood vessel endothelium and smooth muscles, at least one additional pharmaceutical composition comprising a β_2-agonist, and optionally at least one pharmacological agent that induces the promoter to express β_2ARs in the target cells. The pharmaceutical compositions are in a formulation suitable for aerosol delivery or intravenous delivery.

The present method further is directed to an *in vitro* method of expressing the β_2AR gene and evaluating the effect of pharmacological compositions on the expression of β_2ARs in mammalian cells that are transduced with a recombinant vector that carries the nucleic acid sequence encoding the native β_2AR or a modified β_2AR.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts the β_2-AR life cycle following agonist binding to the receptor.

Figure 2 depicts a representation of the a mechanism by which relaxation of airway smooth muscle is induced by β_2-agonists.

Figure 3 depicts transcriptional regulation of the β_2-AR gene expression by glucocorticoids.

Figure 4 depicts AAV vectors and complementor genomic structure. The four phenotypic regions of AAV are shown. The rep region encodes products required for AAV DNA replication. The lip and cap regions encode the virion capsid proteins. The terminal repeats (tr) are required in *cis* for AAV replication, packaging and integration into host DNA. P5 is the AAV promoter. d13-94 and dl6-95 are used as backbones for insertion of the β_2AR and neomycin genes. dl6-95/GFP/Neo and dl6-95/LacZ/Neo are used in experiments to optimize conditions for expression of viral vectors and localization of transduced cells in the rat lung. ins96-λ-M are used to package recombinant AAV vectors.

Figure 5 shows the transduction of SPOC1 cells by AAV-GFP. Panels A and B, SPOC1 cells infected with recombinant AAV (dl6-95/GFP/Neo) observed using fluorescence microscopy, Panels C and D, the same cells observed using interference contrast microscopy.

Figure 6 depicts the genomic structure of recombinant AAV vectors. For reference, the genomic structure of wildtype AAV is shown at the top. Descriptions of each vector can be found in the text. β_2AR(tag) refers to a cassette that contains the β_2AR coding region with an epitope (YPYDVPDYA) added at the amino terminus of the receptor open reading frame. The epitope tag does not alter β_2AR function[147] and can be detected with a specific antibody.[100]

Figure 7 shows the effect of methacholine on airway resistance in anesthesized Brown-Norway rats. *Panels A and B, A*nimals were injected ip with 0.9% NaCl and two weeks later exposed to nebulized 0.9% NaCl for 30 min. *Panels C and D,* animals were injected ip with 1 mg ovalbumin/200 mg aluminum hydroxide in 0.9% NaCl and two weeks later exposed to nebulized ovalbumin (1 mg/ml). Animals were anesthesized with urethane and placed on ventilators so that airflow (Panels B and D) was constant. Methacholine was administered to the animal in nebulized form. The concentration of methacholine in the solution was 1 mg/ml.

Figure 8 depicts putative glucocorticoid response elements (GRE) in the rat β_2-AR gene. Figure 8A provides a schematic representation of the β_2AR gene. GREs are number and approximate locations are shown. Figure 8B shows the exact locations (+1 is the start of transcription) of the putative GREs. The third column shows the nucleotide sequence of each GRE compared to the MMTV consensus GRE. Underlined nucleotides match consensus. The number of matching mucleotides compared to the consensus GRE are shown in column 4.

Figure 9 shows the expression of β_2AR-luciferase fusion genes in HepG2 cells incubated in the absence or presence of 0.1 μM dexamethasone for 8 hours. HepG2 cells were transiently transfected with pRShGRα, pRSVβ-gal, and either pβ_2AR(-62/+126), pβ_2AR(-152/+126), pβ_2AR(-643/+126), pβ_2AR(-1115/+126), pβ_2AR(-2552/+126), pβ_2AR(-3129/+126), orN-600 prATLUC. Transfected cells were incubated for 48 hours prior to addition of dexamethasone. Luciferase activity for each construct is expressed relative to that obtained with pβ_2AR(-62/+126) in the absence of dexamethasone. Results are expressed as the mean ± S.E.M. from eight independent experiments, each conducted in triplicate. *Significantly ($p<.02$) different by Student's t-test.

Figure 10 shows oligonucleotides used in electrophoretic mobility shift assays and luciferase assays with pT81LUC. Both sense and antisense oligonucleotides were made by Bio-Synthesis (Lewisville, TX). Only the sense oligonucleotides for each complementary pair are shown. Bold nucleotides represent β_2AR gene sequence and italicized nucleotides represent restriction enzyme sites added to facilitate cloning into pT81LUC. Underlined nucleotides represent putative core GRE elements. The mutated nucleotide in the putative core GRE element in GRE_5 is underlined and italicized.

Figure 11 shows the effect of a single point mutation in GRE_5 on dexamethasone inducibility of a β_2AR-luciferase fusion gene. Human HepG2 cells were transiently transfected with pRShGRα, pRSVβ-gal, and either pβ_2AR(-3129/+126) or pβ_2ARm1 (-3129/+126) as described in the specification. After transfection, the cells were incubated for 8 hours in either the absence or presence of 0.1μM dexamethasone and cells were harvested. Values are means±S.E. of data from five independent experiments, each performed in triplicate. Asterisks indicate a significant ($p<0.05$) difference in luciferase activity from untreated and dexamethasone-treated cells as determined by Student's t-test.

Figure 12 shows dexamethasone induction of a heterologous thymidine kinase promoter fused to various glucocorticoid response elements. Plasmid constructs with the luciferase gene under the control of the tk promoter and various putative GREs (see Figure 8 for sequences) were tested for luciferase activity after transfection into HepG2 cells that were co-transfected with pRShGRα. Transfected cells were incubated for 48 hours prior to addition of 0.1 μM dexamethasone. Results are expressed as the mean±S.E. from four independent experiments, each conducted in triplicate. *Significantly ($p<.01$) different by Student's t-test.

Figure 13 shows characterization of HepG2 cell nuclear proteins that interact with GRE_5 by electrophoretic mobility shift assays. HepG2 cell nuclear extract (6 μg) was incubated with radiolabeled GRE_5 in the presence of increasing concentrations (10-, 50-, 100-, 250-, or 500-fold molar excess) of the indicated double stranded oligonucletide.

Figure 14 shows the specificity of the interaction between GRE_5 and human recombinant glucocorticoid receptor by electrophoretic mobility shift assays. Human recombinant glucocorticoid receptor was incubated with radiolabeled GRE_5 in the presence of increasing concentrations (25-, 100-, or 250-fold molar excess) of either unlabeled GRE_5, $m1GRE_1$ (see Figure 10 for sequences).

Figure 15 shows [^{125}I] CYP binding to SPOC1 cell membranes: Saturation analysis. SPOC1 cell membranes were incubated at 37°C for 2 hour with increasing concentrations of [^{125}I] CYP. Nonspecific binding was defined with 0.1 μM (-)-propranolol. Scatchard analysis of specific binding (open circles) demonstrated that [^{125}I]CYP binding was saturable and displayed high affinity. Inset: Direct plot demonstrating total binding (closed circles), non-specific binding (open triangles) and specific binding (open circles).

Figure 16 shows cyclic AMP accumulation in SPOC1 cells in response to isoproterenol in the presence and absence of a phosphodiesterase inhibitor. SPOC1 cells were treated for 10 min at 37°C with either vehicle, 100μM IBMX, 10 μM isoproterenol, or 100 μM IBMX and 10 μM isoproterenol in combination. Cyclic AMP accumulation was measured by radioimmunoassay. Significant differences were determined by one way ANOVA and Neuman-Keuls test.

Figure 17 depicts expression of β_2AR-luciferase fusion genes in SPOC1 cells. SPOC1 cells were transiently transfected with 0.2 μg pRLV-SV40, 1.6 μg pGEM7Zf(-), and 0.2 μg of either pβ_2AR(-283/-95) or pβ_2AR(-3349/-95). Cells were incubated for 8

hours in either the presence or absence of deamethasone. Luciferase activities are expressed relative to that of $p\beta_2AR(-283/-95)$ in the absence of dexamethasone. Results are expressed as the mean ±S.E.M. from five independent experiments each performed in triplicate. *Significantly ($p<.01$) different by Student's t-test.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention is directed to a novel approach for adjunctive treatment of patients having airway and/or vascular diseases, in which dilation of the affected airways or blood vessels would be of benefit to relieve symptoms, in diseases, such as asthma, and pulmonary or systemic hypertension. The present treatment utilizes gene therapy to dilate the airways and blood vessels by providing increased levels of β_2ARs for endogenous hormones, such as epinephrine or norepinephrine. Optionally the β_2AR gene containing vector is administered in conjunction with β_2-agonists to enhance treatment by providing increased levels of β_2ARs for the β_2-agonist to bind. More specifically, a vector comprising a β_2AR gene under the control of regulatory sequences that express the gene in the airway epithelial cells and/or airway smooth muscle cells, is delivered to the patient's airway, and optionally, either simultaneously or sequentially, a β_2-adrenergic agonist is delivered to the patient's airway. Similarly, a vector comprising a β_2-AR gene under the control of regulatory sequences that express the gene in the blood vessel endothelial cells and/or blood vessel smooth muscle cells, is delivered to the patient's blood stream, and optionally, either simultaneously or sequentially, a β_2-agonist is delivered to the patient's blood stream.

In a preferred embodiment, the present invention is directed to a novel adjunctive treatment for patients or human subjects with severe asthma who become hypo-responsive to the bronchodilatory effects of β_2-agonists. The treatment method of the present invention comprises administering a vector comprising the β_2AR gene, and optionally administering a β_2-agonist into the airways of the patient. The vector and the β_2-agonist can be administered simultaneously or sequentially, resulting in the airway epithelial cells being transduced by the vector with the resulting infection of airway epithelial cells lining the patients' airways, and also the infection of the smooth muscle composing the epithelial cell boundary, and possibly even entry into the bloodstream. The β_2ARs are expressed in the transduced cells, providing additional β_2ARs to which the administered β_2-agonist binds.

By the present method of treatment, the airway smooth muscles are relaxed and airway dilation is achieved.

The present invention differs from standard gene therapy approach for treating diseases in that it is not utilized to replace a defective protein with a version of the protein that functions properly. The present invention provides increased numbers of β_2ARs on the surface of the epithelial cells, in addition to the native β_2ARs already present. In the treatment of asthma, there is no evidence that the β_2AR is defective, and that this is the cause of the asthmatic condition. Yet, the β_2AR is an important therapeutic target in the treatment of asthma.

The principal clinical benefits anticipated in asthmatic patients receiving β_2AR gene therapy are: 1) increased sensitivity to the airway relaxing effects of circulating epinephrine and norepinephrine, and inhaled β_2-agonists resulting in decreased dependency upon β_2-agonist medications; and 2) decreased susceptibility to the development of subsensitivity or tolerance to inhaled β_2-agonists. The asthma treatment of the present invention is effective in decreasing the incidence of worsening asthma control and mortality that is associated with frequent use of β_2-agonists in some patients who are frequent users of β_2-agonists and suffer from the negative effects of tachyphylaxis.

The present invention also is directed to the use of an inducible β_2-AR gene that is targeted to airway epithelial and/or smooth muscle cells to dilate the airways by increasing the number of β_2-ARs, but also is useful to improve airway responsiveness to β_2-agonists. The use of gene therapy for the management of individuals, whose asthma is poorly controlled by current conventional treatment methods, provides a useful and innovative treatment to overcome desensitization to β_2-agonists. The present invention is built upon the kinetic relationship between β_2-agonists and β_2-ARs to produce beneficial physiological responses (e.g., bronchodilation).

The present invention discloses a new therapy that provides a means to increase β_2-adrenergic responsiveness by increasing levels of β_2AR in airway epithelial cells and/or airway smooth muscle cells. This is accomplished in a step-wise fashion, that in addition to creating a novel approach to treating asthma, advances basic knowledge in research in lung biology. Although the airway smooth muscle possibly represents a more physiologically significant target for gene therapy involving the β_2AR, the present invention focuses on

airway epithelium for several reasons. First, there is evidence that part of the airway relaxing effects of β_2-agonists are mediated via interactions with epithelial cell β_2ARs. Second, airway epithelial cells are easily targeted using vectors derived from either adenoviruses or adeno-associated viruses (AAV). Moreover, the feasibility of transducing epithelial cells with recombinant viruses carrying a mammalian gene and achieving expression of a functional protein has been demonstrated by numerous cystic fibrosis laboratories working with the CFTR protein.[26] This is a procedure that has been used in humans. Third, the present invention provides a practical procedure for specifically targeting and/or expressing a recombinant gene in airway epithelial cells and smooth muscle cells that can be safely used in humans.

The vector and the β_2-agonist is administered simultaneously or sequentially, but preferably the vector comprising the β_2AR gene is administered, and the airway epithelial cells and/or smooth muscle cells are transduced, resulting in the infection of airway epithelial cells and/or smooth muscle cells. The vector containing the β_2AR gene is administered to the subset of asthmatic patients, who are difficult to manage with traditional therapies (e.g., the ones that end up in the emergency room). The recombinant β_2AR vector is administered in aerosolized form, in the same manner that β_2-agonists and glucocorticoids are taken by asthmatics.

Vehicles for gene transfer to cells may be selected from retroviruses, adenoviruses, AAV or nonviral vehicles. But the present invention prefers AAV vectors as the vehicle for transduction. Examples of U.S. patents, disclosing viral transduction of genes using AAV based vectors are U.S. 5,670,488; U.S. 5,139,941 and U.S. 5,252,479. An example of non-viral transfection of lungs is disclosed in U.S. 6,022,737.

After a sufficient period to allow for the transduction of the epithelial cells and the expression of the β_2ARs in the epithelial cells, for example for approximately 1 to 2 days, the β_2-agonist is optionally administered. During this period of time, there is episomal expression that is transient. Long-term expression occurs as the recombinant virus integrates into the host genome. This occurs in a specific location on human chromosome 19. Increased levels of β_2AR are present in infected cells over the course of the cell's lifetime, approximately 180 days in human airways. During that time period, individuals administered the vector containing the β_2AR gene are hyperresponsive to aerosolized β-adrenergic agonist, compared to individuals not given the vector. Eventually, the beneficial

effect diminishes as the airway epithelial cells slough off, divide, and otherwise disappear from the airway. Thus, it is necessary to reinfect a human subject or patient with the recombinant β_2AR vector if control of the patient's asthma becomes difficult again. The persistence of AAV vectors in animals has been studied.[60, 172]

The vector may optionally contain a DNA sequence encoding a mutant or modified β_2AR that is modified as compared to the native β_2AR or wild-type β_2AR. The modified β_2AR possesses at least one property that is different from the native β_2AR. For example, the modified β_2AR may possess increased responsiveness to β_2AR agonists, increased affinity to β_2AR agonists, and/or the capability to increase the potency of β_2AR agonists to simulate downstream signal transduction pathways, as compared to the native β_2AR. The modified β_2AR is modified from the native β_2AR by any one of or a combination of the following modifications, to include deletion of amino acids, substitution of amino acids, and/or replacement of amino acids. The modified β_2AR is produced by modifying the DNA sequence encoding the β_2AR prior to inserting the sequence into the vector.

For example, β_2AR mutants within the scope of the present invention are mutant β_2ARs with phosphorylation sites removed or a constitutively active mutant β_2AR.

A mutant β_2AR with phosphorylation sites removed is useful in the present invention. After binding hormone, the β_2AR rapidly loses its ability to respond to subsequently administered hormone. This process is commonly referred to as desensitization. Desensitization is mediated by G-protein-coupled receptor kinases (GRK) and arrestins. Following hormone binding, the β_2AR is phosphorylated by a GRK which in turn leads to binding of arrestin. The binding of arrestin has two effects on β_2AR function, both of which diminish responsiveness to β_2-agonists. First, arrestin associated with the β_2AR prevents the β_2AR from interacting with the stimulatory guanine nucleotide regulatory protein G_s and activating downstream signaling events. Second, arrestin binding to the β_2AR increases the likelihood that the receptor will be removed from the cell surface and internalized. This reduces the total number of β_2AR on the cell surface and reduces the responsiveness of the cell to β_2-agonist. Based on all of this information, the removal (or replacement) of the amino acids of the β_2AR that are phosphorylated by GRK prevents the process of desensitization. This concept is similar to related receptors for other hormones.[173] To prevent phosphorylation of the β_2AR by GRK, the receptor is either

truncated (e.g., remove a portion of the carboxy tail that contains the phosphorylation sites or replace the serine and theronine residues in the carboxy tail with alanine and glycine residues. The amino acids serine and theronine are phosphorylation substrates.[173, 174]

Constitutively active mutant β_2ARs are also useful in the present invention. Normally, in order to observe activation of downstream signal transduction pathways (activation of adenylyl cyclase and cyclic AMP production) by the β_2AR, hormone must bind to the receptor. However, a report was published several years ago that reported a mutant β_2AR that activated adenylyl cyclase constitutively.[175] The mutant was created by replacing the carboxy terminal portion of the third intracellular loop of the β_2AR with the corresponding region of the α_{1B}-adrenergic receptor, a related receptor subtype that also binds epinephrine and norepinephrine. The resulting mutant receptor was expressed in COS-7 and CHO cells in vitro and tested for activity. The constitutively active β_2AR displayed the following characteristics: 1) an increased affinity for agonists, and 2) increased potency of agonists in stimulating adenylyl cyclase activity. Both effects are desirable in the present invention.

The vector of the present invention contains a promoter that is operably linked to the β_2AR gene and is functional in the cells to which the vector is administered. These cells include the airway epithelial cells and smooth muscle cells and the blood vessel endothelial cells and smooth muscle cells. Preferably, the promoter is a viral vector promoter or a mammalian cell specific promoter. If the promoter is a mammalian cell specific promoter, it is preferably is an epithelial cell specific promoter, an endothelial cell specific promoter, or a smooth muscle cell specific promoter. For example, a promoter was developed that directs expression of the human cystic fibrosis transmembrane conductance regulator gene to airway epithelial cells.[21]

The preferred promoter is a viral vector promoter, which is functional in mammalian cells including either epithelial, endothelial or smooth muscle cells. Examples of such viral promoters are a cytomegalovirus (CMV) promoter or an adeno-associated vector (AAV) promoter. More preferably the vector is an AAV vector containing a CMV promoter. The promoter is selected to obtain the maximum expression of the β_2AR gene in the transfected cells.

The promoter may alternatively be an inducible promoter that allows the regulation of the amount of receptor that is expressed. Such a promoter can be induced or upregulated

by hormones or by other pharmacological agents. The inducible promoter preferably should be a weaker promoter, such as the endogenous β_2AR gene promoter or a tissue-specific promoter. The present invention is intended to encompass the administration of the inducer of the promoter to a human subject to induce the expression of β_2ARs in the target cells. The administration of the inducer in a pharmaceutical composition occurs at the same time that the vector comprising the DNA sequence encoding a β_2AR operably linked to the β_2AR endogenous promoter or a tissue-specific promoter so that the β_2AR gene is expressed. However, after the target cells are transduced and stably carrying the β_2AR gene, to obtain increased β_2AR expression in the target cells, it may be necessary to administer only the inducer or the inducer in combination with the β_2-agonist, to provide enhanced dilation of the airways or blood vessels of the subject.

Suzuki *et al.*[137] provide an example of a regulatable promoter that can be upregulated by exogenous agents that raise the intracellular levels of cAMP. In addition to a promoter, the vector optionally may contain at least one enhancer or regulatory element that allows the β_2AR gene to be turned on or off in the target cells. Burcin *et al.*[176] discloses a regulator to a liver-specific promoter.

The application of gene therapy to treat human disease, while relatively simple in concept, is composed of series of challenges and problems that must be solved before beneficial effects can be realized. Two forms of gene therapy are currently used, *ex vivo* and *in vivo*. In *ex vivo* gene therapy that has been used in cancer patients[144], cells are removed from the patient, transfected with the transgene and then re-implanted into the patient. Gene therapy for tissues that cannot be easily removed from the patient and re-implanted requires using *in vivo* gene therapy.[146] Airway epithelium falls under the second category making *in vivo* gene therapy the required route of administration. Because all viruses transfer and express genetic material during their life cycles, they have frequently been used as vectors in *in vivo* therapeutic gene transfer protocols. Using treatment of cystic fibrosis patients with the cystic fibrosis transmembane conductance regulator (CFTR) gene as a model, several human gene therapy trials have shown that is possible to obtain expression of transferred genes to humans by a number of *in vivo* strategies[26]. The three principle viral vectors used in cystic fibrosis therapy have been retroviruses, adenoviruses, and adeno-associated viruses. Each has its advantages and disadvantages.[43,44] The present inventors have chosen an AAV vector because of 1) natural tropism towards airway

epithelium, 2) efficient integration into the genome of nondividing cells, 3) lack of association with any known human disease, and 4) ability to express the transgene long-term without inactivation *in vivo*.

Recently, there has been increasing use of AAV in human gene therapy protocols. Currently, AAV is being tested in Phase I clinical trials with cystic fibrosis patients at the University of Florida and Johns Hopkins University. Initially, it appeared that there are no deleterious effects to overexpression of the CFTR protein in transgenic animals,[137] and therefore in early gene transfer approaches to cystic fibrosis the prevailing strategy was to express as much CFTR as possible. Therefore many transgenes were typically driven by strong viral promoters to obtain maximal expression levels.[137] More recently it has been recognized that the use of regulatable promoters may be a useful approach to increase safety and/or efficacy in human gene therapy protocols.[51,61,137] Consequently, the present invention is intended to encompass the use of a regulatable promoter featuring a GRE to drive expression of the β_2AR transgene. The β_2AR gene is relatively small (~2 kb) and has no introns. The entire transcription cassette that is inserted in AAV, including the β_2AR gene and the neomyocin resistance gene, is approximately 3.6 kb, well under the packaging limit of 5.2 kb for efficient replication of AAV.[63]

The present vector and methods also are useful in treating vascular diseases. Vascular tone of the pulmonary arteries is a consequence of pulmonary vasorelaxation and vasoconstriction.[177, 178] The pulmonary vasculature expresses both α-adrenergic receptors and β-adrenoreceptors, both of which help to regulate pulmonary vascular tone by producing vasoconstriction or vasodilation, respectively.[179] Pulmonary hypertension starts out with vasoconstriction of the small and medium size pulmonary arteries. As pulmonary hypertension progresses, there is vascular remodeling as a result of smooth muscle hypertrophy. At the level of the pulmonary arteries, there are only two cell types that have any known effect on arterial diameter: smooth muscle cells and endothelial cells. Vasorelaxation is achieved through pathways that are dependent or independent of the endothelial cells. The β_2-agonist, isoproterenol, produces vasorelaxation by interacting with β_2ARs on pulmonary vascular smooth muscle cells. Other agents, such as acetylcholine, produce vasorelaxation by stimulating endothelial cells to produce nitric oxide, which in turns, causes vascular smooth muscle cells to relax. The reason typical vasodilators such as β_2-agonists cannot be used to treat pulmonary hypertension is that they

also cause arteries in the systemic circulation to dilate. This causes a precipitous drop in blood pressure and would lead to circulatory shock and death. The administration of β_2AR containing vector to the smooth muscle cells of the pulmonary arteries is the appropriate method, which results in increased β_2AR levels in these cells, making them more sensitive to circulating β_2-agonists. Low doses of β_2-agonists optionally are given, which cause pulmonary artery smooth muscle cells to relax, and thereby increase arterial diameter and reduce pulmonary arterial pressure. At this low dose of β_2-agonist, the dose is too low to appreciably affect the β_2ARs in the peripheral circulation detrimentally.

To target the vector containing the β_2AR gene to the pulmonary arterial smooth muscle cells, it is injected into a vein, for example the jugular vein. Venous blood returns to the right heart. This blood is then pumped to the lungs where it is oxygenated. Although the endothelial cells form a fairly tight barrier to the diffusion of anything including viruses, an appropriately designed gene delivery vehicle would transport the vector to the targeted cells.

The examples set forth below serve to further illustrate the present invention in its preferred embodiments, and are not intended to limit the present invention. The examples utilize specific vectors and nucleic acid sequences but it is intended that the vectors and nucleic acid sequences with similar functional properties are also intended to be encompassed by the present invention.

Experimental Examples

Construction of AAV Vectors

System for Producing Recombinant Adeno-Associated Virus

Viral vectors and their application to gene therapy are known. The original gene mapping and phenotype determinations in AAV,[64] were first published using recombinant AAV to transduce mammalian cells *in vitro*,[62] and reported transduction of of hematopoietic stem cells with recombinant AAV,[76] and reported the maximum packaging capacity of AAV.[63] Several AAV genomes are useful as vectors to transfer genes into mammalian cells (Figure 4). These include dl3-94 which includes the terminal repeats, poly [A^+] motif, and a unique *BglII* cloning site,[64] dl6-95 which includes the same features as dl3-94 plus the AAV P5 promoter[64] which allows constitutive expression of inserted transgenes. dl6-95/LacZ/Neo allows color selection and dl6-95/GFP/Neo allows expression of green

fluorescent protein for detection of infected living cells. The AAV terminal repeats are the only *cis* sequences in the AAV genome that are required for DNA replication, packaging and integration into the host genome. Approximately 5 kb of DNA can be packaged into dl6-95 and dl3-94.[63] The Neo cassette can be removed and replaced with "filler DNA" for applications in which neomycin expression is not desirable (*e.g.*, *in vivo* transduction of airway epithelial cells).

For generating recombinant AAV stock, a system was developed by Hermonat and Muzcyzka[62] which uses a "wild-type", replication competent AAV genome called ins96-λ-M (U.S. 5,139,941) (see Figure 4 for structure). This AAV variant contains a 1.1 kb λ phage DNA insert at map unit 96 and consequently is too large to be packaged effectively, but promotes packaging of recombinant AAV. This system produces consistently high titers of recombinant AAV (~10^5-10^6 IU/ml compared to ~10^3-10^5 IU/ml) when a non-replicating complementor AAV is used.[122] Using this method, wild-type AAV is produced at a level that is ~10-20% of that of recombinant AAV, an outcome that is not desirable in preparing recombinant AAV for human trials. However, in experiments presented herein, the presence of low levels of wild-type AAV will not affect the outcome of our experiments.

Improvements in vector titer and purity are necessary for use in human gene therapy applications. A method of recombinant adeno-associated virus production has been described that is completely free of helper adenovirus.[165] Use of this method to produce recombinant adeno-associated virus is advantageous in that a more defined reagent will result that is less likely to produce a host immune response. Further improvements in the methodology for recombinant adeno-associated virus preparation are likely as use of the vector in human gene therapy increases.

It is recognized that there are alternative ways to construct recombinant AAV vectors but for maximal expression of the β_2AR, a viral promoter is preferred, such as the CMV promoter or the AAV P5 promoter; or for inducible expression, the endogenous β_2AR promoter, together with the composite GRE identified in this application is selected. The AAV P5 promoter is small and is contained as a convenient cassette with the AAV replication origin and the AAV terminal repeats (TR) which must be included in any AAV-transducing vector.[94] Many other constitutive promoters (*e.g.*, SV40, RSV-LTR) also are useful in the present invention. The β_2AR transcription cassette can be modifed by altering

the sequence, and the number of GREs as well as adding other transcriptional elements to improve inducibility. The β_2AR promoter may be modified to include an epithelium-specific expression cassette.[21] This cassette includes regulatory elements from the human cytokeratin gene. It has been used to efficiently express reporter genes as well as the human cystic fibrosis transmembrane conductance regulatory protein (CFTR) in airway epithelial cells.[21] Other useful promoters that drive β_2AR expression are the human surfactant protein C promoter or the CC10 promoter. These promoters have been used to drive β_2AR gene expression in the airways of transgenic mice.[89] Any human promoter effective in the rat-derived SPOC1 cell line is useful in the present invention. Because AAV displays tropism for airway epithelium, an epithelial cell-dependent promoter is not necessary in order to achieve expression of the β_2AR transgene in airway epithelial cells. In fact, adeno-associated viruses have been used to transfer the CFTR gene into airway epithelial cells.[43,44,45] SPOC1 cells are derived from airway epithelium and are readily infected by AAV. However, alternative methods to transfer DNA into cells also are used. These include using adenovirus, used to transfer the CFTR gene to airway epithelium,[54] guanidinium-cholesterol cationic lipids[108] or by targeting the polymeric immunoglobulin receptor.[41] Finally, radioligand assays and cyclic AMP radioimmunoassays are routine procedures to assess the functional outcome of β_2AR overexpression in SPOC1 cells.

Specific Methods

AAV Constructs containing Rat β_2AR Gene

To study transcriptional regulation of β_2AR gene expression, a rat β_2AR genomic clone was inserted into the *Eco*RI site of λ phage Charon 4A from Dr. P. Buckland, University of Wales. The clone includes the 4190 bp section submitted to the Genebank/EMBL database,[16] plus an additional unsequenced section of aproximately 1400 bp in the 5'-flanking region.

Cell Culture: Tracheal Epithelial Cell Line SPOC1 and 293 Cells

The rat tracheal epithelial cell line, SPOC1, are used for experiments described in this section and are maintained in cell culture as described herein. The human kidney carcinoma derived 293 cell line is maintained in Iscove's modified Dulbecco's media supplemented with 10% fetal bovine serum. Preliminary experiments are conducted in order to establish the optimal conditions for infection of SPOC1 cells with AAV.

Generation of SPOC1 Cells Expressing Green Fluorescent Protein

Optimal conditions for infection of SPOC1 cells with AAV are established using a recombinant AAV that expresses green fluorescent protein. This construct, dl6-95/GFP, expresses green fluorescent protein under the control of the viral P5 promoter.[158] SPOC1 cells are infected with dl6-95/GFP at a multiplicity of infection (MOI) of at least 1. Forty-eight hours post infection, cells are observed using a Zeiss Axiovert inverted microscope equipped for epifluorescence illumination with Hammamatsu chilled CCD and Contax 35 mm cameras for image collection in order to determine the transduction frequency. For time-lapse imaging of living cells, the microscope is also fitted with Bioptechs culture dish and objective temperature controllers. Digital image acquisition is controlled with Cell Robotics Workstation software. To prevent photobleaching, a filter wheel is programmed to block the excitation illumination between exposures.

Expression of Green Fluorescent Protein (GFP) in SPOC1 Cells Transduced with Recombinant AAV Carrying the Green Fluorescent Protein (GFP) Gene

SPOC1 cells were infected with dl6-95/GFP/Neo which expresses green fluorescent protein under the control of the viral P5 promoter (Figure 4). Seventy-two hours post infection, cells were observed using a Zeiss Axiovert inverted microscope equipped for epifluorescence illumination. Cells were observed using both interference contrast and epifluorescent illumination. As shown in Figure 5, transduction of SPOC1 cells by recombinant AAV was relatively efficient. Panels A and B show fluorescent images obtained from two different groups of cells. GFP fluorescence was observed in a mostly diffuse pattern throughout the cytoplasm (Figure 5). The same cells visualized by interference contrast microscopy are shown in Panels C and D (Figure 5). Overall, greater than 50% of the cells were transduced by the recombinant AAV as judged by GFP fluorescence. These results demonstrate that the SPOC1 cell line can be transduced by AAV.

Preparation of Recombinant AAV Containing a β_2AR cDNA

Four different recombinant AAV vectors (for structures see Figure 6) are prepared. As an example, only the construction of one recombinant AAV vector, dl6-95/β_2AR/Neo^{SV40}, is described here. The starting point is pdl6-95PL1 which contains the AAV terminal repeats, the AAV P5 promoter, and a polylinker with multiple cloning sites with two interspersed poly [A$^+$] signals. Into this plasmid is inserted the Neo gene to form

the parental plasmid, pdl6-95/Neo, which contains an SV40 EPR-NeoR transcription cassette on a 1.2 kb *Xba*I fragment ligated into the *Xba*I site of pdl6-95PL1 (both pdl6-95PL1 and pdl6-95/Neo obtained from Dr. Hermonat). The *Nde*I end of a 1.7 kb *Hind*III/*Nde*I fragment encoding the rat β_2AR is converted into a *Hind*III site with a linker for cloning into the *Hind*III site of pdl6-95/Neo. Recombinants are sequenced in order to identify clones with the β_2AR coding sequence is in the proper orientation. The combined size of Neo and the β_2AR sequence, approximately 3.6 kb, is well under the maximum insert size for efficient AAV replication.[63] The construct is transformed into competent *E. coli* and positive clones selected and purified using a plasmid mini-prep kit (Promega, Madison, WI).

The four types of recombinant AAV vectors are prepared, all of which will include the coding region of the β_2AR (see Figure 6 for structures): 1) dl6-95/β_2AR/Neo^{SV40}, 2) dl3-94/β_2AR/Neo^{SV40}, 3) dl6-95/β_2AR(tag)/Neo^{SV40}, and 4) dl3-94/β_2AR(tag)/Neo^{SV40}. Constructs dl6-95/β_2AR/Neo^{SV40} and dl6-95/β_2AR(tag)/Neo^{SV40} include the rat β_2AR cDNA whose expression are under the direction of the AAV P5 promoter which allows high-level, constitutive expression of the β_2AR in infected SPOC1 cells. Constructs dl3-94/β_2AR/Neo^{SV40} and dl3-94/β_2AR(tag)/Neo^{SV40} include the β_2AR cDNA whose expression is under the direction of the β_2AR promoter and the composite GRE previously identified. Expression of these transgenes enable regulation of expression by glucocorticoids. Two constructs carry the β_2AR cDNA with an epitope tag attached to the carboxy terminus to allow recombinant β_2AR to be distinguished from native β_2AR. All AAV vectors will carry the Neo gene under the control of the SV40 early promoter to allow selection of AAV-infected SPOC1 cell colonies under the antibiotic G418. SPOC1 cells are transduced with these vectors, then assays (radioligand assays, cyclic AMP determinations) are performed to assess levels and function of expressed β_2ARs. Radioligand assays are performed to establish the total number of β_2ARs (native and recombinant) on SPOC1 cell surface. Levels of recombinant β_2AR are determined by antibody detection of the epitope tag. Functional coupling of SPOC1 cell β_2ARs to downstream signal transduction pathways are assessed by a cyclic AMP radioimmunoassay.

The inducibility of dl3-94/β_2AR/Neo^{SV40} and dl3-94/β_2AR(tag)/Neo^{SV40} are tested by incubating SPOC1 cells infected with these vectors with the synthetic glucocorticoid

dexamethasone. Radioligand assays and antibody detection of the epitope-tagged β_2AR are performed to determine β_2AR levels in transduced cells. Cyclic AMP radioimmunoassays are performed to determine functional coupling of expressed β_2ARs.

Packaging and Titering of Recombinant AAV Virus Stocks

Recombinant virus stocks are generated using the AAV complementor genome ins96-λ-M as previously described.[62] This complementor genome has all the AAV genes and regulatory sequences necessary for replication, but has a 1.1 kb λ phage insert located in a non-essential site at map unit 96. Because of the presence of the insert, the ins96-λ-M genome is inefficiently packaged into virions, but recombinant AAV is packaged. Low levels of wild-type AAV are produced by this procedure, an inconsequential outcome since AAV is non-pathogenic. Detailed methodology can be found in Hermonat and Mazyczka.[62] Briefly, recombinant vector plasmid (5 μg) are DEAE/Dextran transfected along with ins96-λ-M plasmid into 293 cells. Various cell lines can be used for packaging, but 293 cells display a high efficiency of transfection.[2] Cells are then infected with AAV type 2 at a MOI of 5. Forty-eight hours later, at maximum cytopathic effect, the cells are lysed by freeze-thawing the plates three times, followed by heating to 56°C to kill the virus. After a low-speed centrifugation to remove cellular debris, a homogeneous recombinant vector preparation free of wild type AAV is obtained by multiple $CsCl_2$ equilibrium gradient centrifugations. Recombinant virus stocks are titered by performing Southern blot hybridization of isolated single-stranded vector DNA to determine copy number of packaged genomes[122] and by comparing the generation of G418 resistant colonies of the untitered virus stock compared to that of known titers of wild type AAV virus stock.[62]

Infection and Selection of SPOC1 Cells

The recombinant AAV viruses are used to infect SPOC1 cells at a MOI of either 1 or 10. In addition, SPOC1 cell cultures are mock-infected. Cells are exposed to virus for 1 hr at 37°C and then plated in 2 ml of media for continued culture at 37°C. G418 (final concentration = 400 μg/ml) is added to the medium 48 hr after infection. After three weeks of G418 selection, neomycin resistant cells are cloned and expanded. To determine if stable integration of the β_2AR gene is present in G418 selected SPOC1 cells, DNA is extracted, digested with *Hind*III and *Bgl*II and Southern blot analysis is performed using

standard methods.[86] Detection of a ~1.7 kb fragment that hybridizes with a radiolabeled β_2AR cDNA would indicate stable integration of the recombinant β_2AR gene.

Epitope-Tagged β_2-Adrenergic Receptor

Because SPOC1 cells express a wild-type β_2AR, it is useful to have a method to detect the expression of recombinant β_2AR in clonal lines infected with recombinant AAV. To accomplish this, an epitope-tagged β_2AR is used. The cDNA encoding the rat β_2AR are modified by insertion of the sequence encoding YPYDVPDYA at the amino terminus of the receptor by oligonucleotide-directed mutagenesis. This modification has been performed on the human β_2AR and has been shown to not alter expression or function of the receptor.[147] This nine amino-acid epitope is recognized by the antibody 12CA5.[100] Thus, immunoblot analysis of membrane fractions prepared from SPOC1 cells can be used to detect recombinant receptor. Membrane fractions from infected SPOC1 cells are resolved on 10% SDS polyacrylamide gels, transferred to nitrocellulose filters (Schleicher and Schuell, Keene, NH). Immunoblotting is performed in 5% nonfat dry milk containing 2% Nonidet P-40 as previously described using primary antiserum at 1/600 and horseradish peroxidase-conjugated second antibody.[147] The presence of recombinant β_2AR in clonal cell lines infected with recombinant AAV vector was detected, whereas mock-infected cells did not express the epitope-tagged β_2AR.

Treatment of SPOC1 Cells with Dexamethasone

Two of the β_2AR transgenes that are under the control of the β_2AR gene promoter plus the composite GRE is inducible by dexamethasone. Clonal SPOC1 cells that had been infected with either the AAV vector dl3-94/β_2AR/Neo^{SV40} or dl3-94/β_2AR(tag)/Neo^{SV40} and mock infected cells are treated with either vehicle or 0.5 μM dexamethasone for 12 hours. Membrane fractions are prepared in order to determine β_2AR number. In separate experiments, cells subjected to the same treatments are treated with (-)-isoproterenol and cyclic AMP concentrations determined by radioimmunoassay. In experiments with SPOC1 cells infected with dl3-94/β_2AR(tag)/Neo^{SV40}, levels of the epitope-tagged β_2AR are determined by immunoblots. β_2AR levels and β_2AR-stimulated adenylyl cyclase activity is increased in cells treated with dexamethasone. These experiments are repeated six times with six different cell platings to perform statistical analysis of the results.

β_2-Adrenergic Receptor Radioligand Assays

In order to determine levels of β_2AR expression in clonal SPOC1 cells, radioligand assays with [^{125}I] cyanoiodopindolol ([^{125}I]CYP) are performed. Partial purified membrane preparations are obtained from mock-infected and clonal SPOC1 cells by differential centrifugation essentially as previously described.[104] Briefly, cells are washed with ice-cold phosphate buffered saline (PBS) and scraped into ice-cold PBS with a rubber policeman. The cells are centrifuged at 250x g for 5 min, resuspended in assay buffer (50 mM Tris HCl, pH 7.4, 2 mM $MgCl_2$), and homogenized with a glass-glass homogenizer followed by sonication (five 10 second bursts at setting 6) with a Tekmar Model AS1 Sonic Disrupter. The nuclei are removed by centrifugation at 600x g for 10 min. The membranes are obtained from the resulting supernatant by centrifugation at 30,000x g for 15 min. The membranes are resuspended in assay buffer and centrifuged again at 30,000 g for 15 min. The final pellets are resuspended in assay buffer, aliquoted and stored at -80°C until used for radioligand assays. Protein concentrations of membrane preparations are determined by the method of Bradford[11] using bovine serum albumin as the standard. Typically, ~70 μg of membrane protein from SPOC1 cells is obtained that are at 80% confluency in 100 mm dishes. Thus, six plates yield sufficient membrane protein in order to perform either one saturation experiment or a single competition curve. [^{125}I]CYP (Dupont-NEN, Boston, MA; specific activity = 2200 Ci/mmole) are used to identify β_2ARs as previously described.[87] In saturation experiments, aliquots of SPOC1 cell membranes (final protein concentration in the assays tube = 16 μg/ml) are incubated with eight different concentrations of [^{125}I]CYP ranging from 0.5 to 80 pM. Nonspecific binding is defined with 0.1 μM (-)-propranolol. Data from saturation experiments are analyzed using the LIGAND program to obtain binding site concentration and the dissociation constant for [^{125}I]CYP. Since [^{125}I]CYP cannot distinguish between native and recombinant β_2AR, observed increments in total β_2AR levels in clonal cells compared to that in mock-infected SPOC1 cells are attributed to arising from the virally-introduced recombinant β_2AR gene. In order to characterize pharmacologically the expressed recombinant β_2AR in clonal SPOC1 cells, competition experiments with β-adrenergic agonists and antagonists are performed. In competition experiments, aliquots of SPOC1 cell membranes (final protein concentration in the assay tube = 16 μg/ml) are incubated with a single concentration of

[^{125}I]CYP (~1 pM) and increasing concentrations of the competitor. Inhibition constants for agonists and antagonists are calculated using the method of Cheng and Prusoff[20] and are compared with that of wild-type β_2AR. Saturation and competition experiments with each agonist and antagonist are performed six times with different membrane preparations in order to obtain accurate estimates of binding site concentration and inhibition constants for agonists and antagonists. The results of these experiments show the [^{125}I]CYP binding site in clonal SPOC1 cells as the β_2AR subtype.

Cyclic AMP Radioimmunoassay

In order to determine if the recombinant β_2AR expressed in clonal SPOC1 cells is able to functionally couple to adenylyl cyclase, cyclic AMP radioimmunoassays are performed using lysates. Mock-infected and clonal SPOC1 cells are plated at a density of 100,000 cells/well in 12-well dishes (Costar, Cambridge, MA). Cells are treated with adrenergic agonists and the phosphodiesterase inhibitor isobutylmethylxanthine (IBMX) for 10 min. Cellular cyclic AMP levels are determined by radioimmunoassay using the Biotrak CAMP Assay System (Amersham Life Science, Arlington Heights, IL). Agonist-stimulated cyclic AMP accumulation will indicate that surface β_2ARs are functionally coupled to adenylyl cyclase. Clonal SPOC1 cells overexpressing β_2AR would be expected to display increased sensitivity to β-agonist stimulated cyclic AMP formation. These experiments are repeated four times with four different SPOC1 cell platings.

AAV Constructs Containing the Human β_2AR Gene

Construction of an AAV-Human β_2AR Vector

Polymerase chain reaction (PCR) was performed on human genomic DNA known in the prior art,[73, 171] to obtain the β_2AR gene, using a forward primer engineered with a *Hind*III restriction endonuclease cut site 5' of the ATG, and a reverse primer engineered with a *Bam*HI restriction endonuclease cut site 3-prime to the stop codon. The PCR product was phenol chloroform extracted twice and chloroform extracted once. Phases were separated by centrifugation in a Phase Lock I Light (5 prime 3 Prime, Inc. cat p1-175850), ethanol precipitated and resuspended in RE buffer E and cut with *Bam*HI and *Hind*III (Promega Corp) for 2 hours at 37°C. The RE digest was cleaned up using the Wizard DNA clean-up Kit (Promega Corp., cat # A7280). The vector used as the recipient of the β_2AR gene PCR product was pCEP4 (Invitrogen, cat # V044-50). This vector

provided the CMV promoter and the SV40pA tail. The insert was directionally cloned into the polylinker region via sticky-end ligation using the 2x rapid ligation buffer and T4 Ligase from the pGem-T Easy Vector System I using protocol instructions from that kit (Promega Corp., cat # A1360).

The CMV promoter - human β_2AR gene - SV40 pA tail moiety was released by digestion with *SalI* restriction endonuclease in D buffer (Promega Corp.) for 2 hours in a 37°C water bath. The digest was run on a 1% NuSieve GTG agarose mini gel (FMC BioProducts, cat # 50081) in 1xTBE buffer at 100 volts for one hour and subsequently stained with ethiduim bromide to visualize the DNA bands. The fragment of choice was excised under minimum UV exposure with a sterile razor blade and the agarose strip was placed in a 1.5 ml microfuge tube and melted in a 65°C water bath for 30 min. The DNA fragment was isolated from the melted agarose using the Wizard PCR Clean-up kit (Promega Corp., cat # A7170).

The AAV vector used to accept the CMV promoter – human β_2AR gene – SV40 polyA tail moiety was pAV53-LR, the cloning vector containing the ITR's from AAV (obtained from Jianyun Dong, University of South Carolina). This vector was linearized with *XhoI* restriction endonuclease in buffer D (Promega, Corp.) for 2 hours in a 37°C water bath. The digest was cleaned up using the Wizard DNA Clean-up kit (Promega Corp. cat # A7280).

The gel-purified *SalI* fragment insert from the pCEP4/human β_2 gene and the linearized pAV53 LR vector were ligated using sticky end ligation protocol from the T Easy Vector System I, (Promega Corp. cat # A1360) overnight at 4°C. (*Xho*I and *Sal*I have compatible ends.)

The size of the insert in pAV53-LR needs to be between 4.0 – 4.8 kb. Up to a 1.9 kb fragment was needed to achieve an insert within the optimal size range. The pEGFP-C1 cloning vector (Clontech Laboratories, Inc., cat # 6084-1) provided sufficient base pairs of the marker gene with it's own promoter and polyA tail to use as a DNA filler insert for the pAV53-LR/CMV-Huβ2AR-SV40pA to obtain an optimal cassette length. The CMV IE promoter, EGFP gene – SV40 poly A tail was PCR-amplified out of the pEGFP-C1 vector using primers (Biosynthesis) engineered with *Sph*I sites in the forward and reverse directions. The PCR product was phenol chloroform extracted and ethanol-precipitated as previously described and resuspended in deionized, double distilled water and subsequently

digested in a 37°C water bath with *Sph*I restriction endonuclease in buffer K (Promega Corp.) and cleaned up using the Wizard DNA clean-up kit (Promega Corp., cat # A7280).

The EGFP insert was ligated to the pAV53 LR/CMV-Huβ_2AR-SV40pA vector, pre-linearized with *Sph*I restriction endonuclease, by sticky end ligation as previously described. This final vector has a 2,610 bases inserted between the ITR's of the pAV53-LR vector. The total DNA cassette length is 4651 base pairs and codes for the human β_2AR and the Enhanced Green Fluorescent Protein.

Adenovirus production

HeLa cells (ATCC cat # CCL-2) are grown in in two 10 ml dishes in DMEM medium (CellGro cat # 10-013-CM) with 10%FBS (Gibco cat # 16000-044) added, and incubated in a 37°C / 5% CO_2 (Forma Scientific water jacketed tissue culture incubator).

Adenovirus stock (AV) obtained from Jianyun Dong, PhD's laboratory at the University of South Carolina was added to infect both plates of 90-95% confluent HeLa cells grown overnight –(25 µl/ 10cm dish, and then incubated at 37°C / 5% CO_2 in a tissue culture incubator for 24 hours. These plates are examined closely over the next 12 hours to determine cytopathic effect (CPE). At approximately 50% CPE, all the media is removed from the plates and washed one time with 10 ml, serum-free DMEM. Then 1 ml of serum free DMEM is added and the cells are harvested to a 1.5 ml eppendorf microfuge tube by gently scraping with rubber policeman. The cells are frozen in liquid N_2 for 2 min and then thawed in 37°C water bath for 3 min. This cycle is repeated for a total of 3 freeze/ thaw cycles to crack apart the cell membranes. The cell membrane debris is pelleted for 5 min and aliquots of the supernatant are collected in 50 µl aliquots and stored at –80°C.

To determine titer of AV harvested above, HeLa cells were grown overnight in 12-well dish at about 80% confluent, in 0.5 ml DMEM/10%FBS medium / well. The next morning, one tube of AV stock was thawed and dilutions made (1:10 and 1:100 in serum-free DMEM). Increasing amounts of diluted AV (2 – 8 µl of 1:10 dilution, and 2 – 50 µl of 1:100 dilution) were added to each of the 12 wells. The cells were placed in the 37°C / 5% CO_2 tissue culture incubator. At 48 hours, the cells were observed, and the wells showing 50% CPE were the optimal amount of AV to use for transfection of the AAV constructs into HeLa cells for the packaging of the AAV.

Transduction of HeLa Cells with the AAV Constructs

HeLa cells were seeded in 6-well plates at approximately 50 – 80% confluency and grown at 37°C / 5% CO_2 overnight. The cells were transfected using the LipofectAMINE plus protocol (Gibco cat # 10964-013) and Optimem transfection medium (Gibco cat # 31985-062). The ratio of helper to AAV vectors was 10:1 as previously determined by Jianyun Dong's laboratory. At the end of the DNA:lipofectamine complexing incubation period, the predetermined amount of diluted AV stock was added to the lipofectamine:DNA complex immediately prior to putting on the cells. The plates of transfecting cells were placed in the tissue culture incubator (37°C / 5% CO_2) for 4 hours. An equal volume of DMEM medium containing 20% FBS was added to each well for a final concentration of 10% FBS, and then incubated for up to 48 hours at 37°C / 5% CO_2. The media was removed and the plates tapped to dislodge cells. The cells were pooled to a 1.5 ml microfuge tube (Sarstedt cat # 72.690) in a total volume of 1 ml serum-free media, and then frozen in liquid N_2 for 3 min, thawed in a 37°C water bath for 3 min, vortexed. The freeze/thaw/vortex cycle was repeated for a total of 3 times. Cellular debris was pelleted in a tabletop microcentrifuge (Eppendorf 5415-C) at room temp for 5 min . The supernatant was transferred to a new 1.5 ml microfuge tube and then stored (4°C for up to one week, or -80°C if to be used later than one week). Note – before freezing: The AV is inactivated by heating the above virus harvest at 56°C for 60 minutes.

The above harvested virus was added directly to overnight growths of SPOC1 cells that were seeded at approximately 85% confluency in defined medium as below:

Base medium is F-12/DMEM (Gibco cat #11320-033)

5μg/ml Insulin (Sigma cat # I 6634)

0.1μg/ml Hydrocortisone (Sigma cat # H 0135)

5μg/ml Transferrin (UBI cat # 04-101)

5ng/ml EGF (UBI cat # 01-107)

0.1μg/ml Cholera Toxin (Sigma cat # C 3012)

50μM Ethanolamine (Sigma cat # E 6133)

50μM Phosphoethanolamine (Sigma cat # P 0503)

15 mM Hepes (Gibco cat # 11344-025)

1.5mg/ml BSA (Sigma cat # A 2934)

30μg/ml Bovine Pituitary Extract (UBI cat # 02-103) filtered through a 0.45 μm CA filter unit (Nalgene cat # 155-0045)

The Hela cells were grown overnight at 37°C / 5% CO_2 and then viewed under a Fluorescent microscope at 24 and 48 hours to determine infection efficiency (MOI) using the marker gene, EGFP which is a part of the AAVβ_2Hu construct.

For the treatment of human subjects, it is important to remove the adenovirus helper prior to administration. The adenovirus can be removed using the methods of U.S. Patent No. 5,139,941, and the new methods of U.S. Patent Nos. 5,945,335; 6004,797 and 6,001,650. The present method is intended to utilize any method or to remove the adenovirus from the AAV-β_2AR stock. Additionally, the described AAV-β_2AR construct is useful to transduce human airway epithelial and smooth muscle cells but contains an inactivated phosphorus fluorescent green protein gene promoter. This protein gene is left in the construct to provide the preferred size of approximately 4.7kb between the ITRs of the AAV vector.

Effect of Airway Epithelial Cell Directed β_2AR Gene Therapy in a Rat Model that Displays Airway Hyper-Responsiveness Following Antigen Challenge

The AAV vectors containing the β_2AR gene described above are used to transduce the epithelial cells of the airways of subjects, including rodents and humans, and the airway responsive is measured.

The studies described herein determine the effect of overexpression of the β_2AR in airway epithelial cells and its beneficial effect on airflow. The Brown-Norway rat was chosen as the experimental model because this inbred strain displays airway hypersensitivity to cholinergic agonists following sensitization and subsequent challenge with ovalbumin. The sensitized Brown-Norway rat is considered a reasonable approximation of the state of airways in atopic asthma.[37] A consideration is that the rats may develop an immunogenic response to the Neo gene product. Since this may result in additional airway inflammation (beyond that caused by the sensitization protocol) and expression of the Neo gene product is not needed in these *in vivo* experiments, the Neo cassette is inactivated by mutating the AUG that encodes the initiator methionine. This will disrupt the open reading frame. Alternatively, the Neo gene cassette is removed and replaced with spacer sequence in order to keep the size of the vector at ~4.5 kb to optimize packaging efficiency. For purposes of clarity, the same nomenclature to describe the

various AAV constructs that are used despite inactivation of the Neo gene cassette. Experiments are conducted to determine expression levels of the β_2AR transcription cassetteare retained. These experiments are performed to confirm that recombinant AAV vectors containing β_2AR transcription cassettes act by increasing recombinant β_2AR protein levels directly rather than by activating expression of the endogenous β_2AR gene. Modifications in the β_2AR transcription cassette optionally may be made to improve expression of recombinant β_2AR in airway epithelial cells.

Four separate studies are conducted to assess the physiological consequences of β_2AR overexpression in airway epithelial cells. The results of these studies determine the effect of β_2AR overexpression on lung function, the duration of the beneficial effect, the extent of recombinant β_2AR induction that can be achieved by administration of dexamethasone, and effect of withdrawal of glucocorticoids on β_2AR expression and lung function.

Specific Methods

Increased Airway Sensitivity to a Methacholine Challenge in the Ovalbumin-Sensitized Brown-Norway Rat

Experiments with control and ovalbumin-sensitized Brown-Norway rats are performed in which the airway sensitivity to a methacholine challenge was determined. Animals are sensitized and challenged. Inbred Brown-Norway rats (8-9 weeks old) are actively sensitized using ovalbumin by a standardized procedure.[117] Briefly, animals are sensitized by a single subcutaneous injection of 1 ml of 0.9% NaCl containing 1 mg ovalbumin and 200 mg aluminum hydroxide. Fourteen days later, animals are challenged with an aerosol of 1% ovalbumin delivered by a Marquest hand-held updraft nebulizer. Rats exposed to a single ovalbumin challenge following sensitization display a significantly increased responsiveness (an increase in measured airway resistance) to inhaled acetylcholine compared with saline-exposed rats.[38] This model of airway hyper-responsiveness has been established as described in the present invention (see, Figure 7).

The protocol used to sensitize and then challenge Brown-Norway rats is the following:[38] Animals were injected with either 0.9% NaCl (control) or 1 mg ovalbumin and 200 mg aluminum hydroxide in 0.9% NaCl (sensitized). Two weeks later, control animals and ovalbumin-sensitized animals were exposed to aerosolized 0.9% NaCl or 1 mg/ml ovalbumin, respectively, for 30 min. The animals were anesthetized and

instrumented exactly as described herein. Data from one control and one ovalbumin-sensitized animal are shown in Figure 7 Animals were placed on ventilators so that air flow is constant (Figure 7B and 7D, bottom panels). With the addition of methacholine, 1 mg/ml in nebulized form (Figures 7A and 7B) airway pressure increases. From the relationship Q = P/R, since flow (Q) is constant the increase in airway pressure must be due to an increase in airway resistance. Examination of the pressure traces, clearly demonstrate increased sensitivity of ovalbumin-sensitized Brown-Norway rats (Figure 7C) to a methacholine challenge compared to the control rats (Figure 7A). These results, consistent with previously published values for methacholine-induced increases in airway resistance in ovalbumin-sensitized Brown-Norway rats,[117] demonstrate a reprodible model. From this data, reversal of methacholine-induced increases in airway resistance are easily measurable in ovalbumin-sensitized Brown-Norway rats that over-express the β_2AR following transduction with recombinant AAV.

Data Analysis

Representative tracings of air flow and pressure from control and ovalbumin-sensitized Brown-Norway rats that were subsequently challenged with aerosolized methacholine are shown in Figure 7. Lung resistance is determined essentially as described[34] after subtracting the resistance of the endotracheal tube. The methacholine concentration given is that required to increase lung resistance to 200% of that measured in vehicle treated animals. Sensitivity to the airway relaxing effect of the β-adrenergic agonist (-)-isoproterenol are determined by administering increasing concentrations of (-)-isoproterenol in a cumulative fashion. Airway resistance are calculated after each dose of (-)-isoproterenol which will allow a dose-response curve to be plotted and an ED_{50} calculated for each experimental animal. Differences between the mean isoproterenol ED_{50} of different experimental groups are compared by ANOVA followed by Newman-Keuls test. The accepted level of significance is .05.

Infection of Brown-Norway Rats with recombinant AAV Vectors

Administration of Recombinant AAV

Approximately 10^{10} AAV particles in 300 µl PBS are instilled intratracheally into anesthetized Brown-Norway rats as previously described.[153] This procedure has been used successfully to achieve high level expression of transforming growth factor-β1 in

bronchoalveolar fluids from rats that had been subjected to adenovirus-mediated gene transfer.[131] Using similar methodology, airway epithelial cells have been transduced by AAV vectors in the rabbit.[60]

Demonstration of AAV Infection Sites by *In Situ* Staining of LacZ

Because Brown-Norway rats have not been extensively used for studies on AAV-mediated gene transfer in the lung, preliminary experiments are performed in which dl6-95/LacZ/Neo^{SV40} instilled intratracheally and 24 hours later the distribution and cellular localization of LacZ determined. A previously described method for histochemical staining for LacZ protein are used,[85] as modified by Xing *et al.*[153] Briefly, 24 hours after infection with dl6-95/LacZ/Neo^{SV40}, animals are anesthetized, and lungs fixed by intratracheal perfusion with 2% formaldehyde containing 0.2% glutaraldehyde in PBS at 4°C. The lungs are rinsed twice by intratracheal perfusion with PBS and stained by intratracheal infusion of a solution containing 5 mM $K_4Fe(CN)_6$, 5 mM K_3Fe_3, 2 mM $MgCl_2$, and 0.5 mg/ml of the X-gal stain (5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside) at 37°C overnight. The stained lung tissues are then embedded in paraffin, sectioned, counterstained with nuclear red fast, and examined under the microscope for product formation. The results of these experiments will determine the major cellular sites of infection by AAV, likely epithelial cells of the small respiratory bronchioles.

Preliminary experiments are performed in which four Brown-Norway rats are infected intrtracheally with a recombinant AAV vector that contains a LacZ transcription cassette (dl6-95/LacZ/Neo^{SV40}). Twenty-four to forty-eight hours later, animals are sacrificed and their lungs sectioned and treated with the substrate 5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside. Sections are observed under the microscope and cells containing blue stain indicate the presence of LacZ. The results from these experiments allow the identification of recombinant AAV infection and the location of infected cells.

Localization of Recombinant AAV Transcription Cassette mRNA by *In Situ* Hybridization

In order to confirm that dl3-94/β_2AR/Neo^{SV40} vector DNA acts by increasing recombinant β_2AR protein levels directly rather than by activating expression of the endogeneous β_2AR gene, *in situ* hybridization is used to determine expression levels of the β_2AR transcription cassette. In addition to β_2AR coding sequence, the recombinant mRNA will have unique sequences (*e.g.*, polylinker and some viral sequence) to which anti-sense oligonucleotides are synthesized. The *in situ* hybridization is performed using anti-sense

oligonucleotides as probes[18,69] and these protocols are used to localize β_2AR transcription cassette mRNA in the lungs of recombinant AAV infected Brown-Norway rats.

Alternative experimental approaches than those described are also within the scope of the present invention. In place of, or in addition to, the experiments in which *in situ* hybridization are used to determine expression levels of the β_2AR transcription cassette, animals are infected with the inducible recombinant AAV vector dl3-94/β_2AR(tag)/Neo^{SV40} or the consititutively expressed dl6-95/β_2AR(tag)/Neo^{SV40}. Expression of the transgene is monitored by immunohistochemistry using a commercially available antibody directed against the tagged epitope as the first antibody. This approach allows expression of the transgene to be localized at the cellular level as well and provides direct evidence that mRNA transcribed from the β_2AR transcription cassette was indeed being translated into protein. Finally, the determination of airway resistance is the most appropriate physiological parameter to measure as a determinant of the beneficial effect of overexpression of β_2ARs in airway epithelial cells. This measurement are sensitive to changes in airway diameter at all levels of the bronchiolar tree. An alternative approach would be to measure contractile activity of excised tracheal segments *in vitro* to determine the ability of a β-adrenergic agonist to relax airway smooth muscle that had been pre-contracted with methacholine. The major cellular sites of infection of the recombinant AAV vectors are in epithelial cells of the small and respiratory bronchioles as was found with infection of rats with recombinant adenoviruses.[153] In the experiments to determine the duration of the beneficial effect of β_2AR overexpression on lung function, the length of the experiment is set to 120 days. The observation is based on that respiratory epithelium has a turnover time (t½) of approximately 100 to 120 days.[9] After 120 days following infection, the beneficial effect of β_2AR overexpression is reduced by approximately 50%. This estimation assumes integration of the transgene into the host cell genome and that a significant population of epithelial stem cells is not transduced.

In situ hybridization is used to determine whether airway epithelial cells of recombinant AAV vector infected rats express the β_2AR transcription cassette. Anti-sense oligonucleotides directed against unique sequences in the cassette are used as probes in lung sections prepared from four mock-infected animals and four animals infected with dl3-94/β_2AR/Neo^{SV40}. Detection of β_2AR transcription cassette mRNA will indicate that the transgene is being expressed.

Effect of β_2AR Overexpression on Lung Function

Sensitized Brown-Norway rats (three groups, five rats in each group) are infected with one of the following recombinant AAV vectors: dl3-94/Neo^{SV40}, dl3-94/β_2AR/Neo^{SV40} or dl6-95/β_2AR/Neo^{SV40}. dl3-94/Neo^{SV40} does not contain a β_2AR transcription cassette, dl3-94/β_2AR/Neo^{SV40} contains a β_2AR transcription cassette driven by the β_2AR promoter with a GRE present, and dl6-95/β_2AR/Neo^{SV40} contains a β_2AR transcription cassette driven by the AAV P5 promoter. Seven days following infection with recombinant AAV, animals are challenged with ovalbumin. Animals are instrumented and the sensitivity to the β-agonist, (-)-isoproterenol (as measured by decreased airway resistance) is determined following exposure to methacholine. The results from this experiment shows the beneficial effect of the overexpression of β_2AR in airway epithelial cells on lung function as measured by changes in airway resistance following β- agonist treatment. Lungs from all experimental animals are removed and stored at -70°C for analysis by either *in situ* hybridization or immunohistochemistry determine the extent of recombinant β_2AR gene expression.

Duration of β_2AR Expression on Lung Function

Sensitized Brown-Norway rats (three groups, 32 rats in each group) are infected with one of the following recombinant AAV vectors: dl3-94/Neo^{SV40}, dl3-94/β_2AR/Neo^{SV40} or dl6-95/β_2AR/Neo^{SV40} Either 1, 2, 7, 14, 30, 60, 90 or 120 days following infection with recombinant AAV, animals are challenged with ovalbumin. Animals are instrumented and the sensitivity to the β-agonist (-)-isoproterenol (as measured by decreased airway resistance) determined following exposure to methacholine. The results from this experiment determine the duration of the beneficial effect of β_2AR overexpression on lung function as measured by changes in airway resistance following β-adrenergic agonist treatment. Lungs from all experimental animals are removed and stored at -70°C for analysis by either *in situ* hybridization or immunohistochemistry determine the extent of recombinant β_2AR gene expression.

Effect of Inducement of β_2AR Expression on Lung Function

Sensitized Brown-Norway rats are divided into six groups with four rats in each group. Group I are infected with dl3-94/Neo^{SV40} and treated with AAV vehicle for 7 days. Group II are infected with dl3-94/Neo^{SV40} and treated with daily subcutaneous injections of

1 mg/kg dexamethasone for 7 days. Group III are infected with dl3-94/β_2AR/Neo^{SV40} and treated with vehicle for 7 days. Group IV are infected with dl3-94/β_2AR/Neo^{SV40} and treated with daily subcutaneous injections of 1 mg/kg dexamethasone for 7 days. Group V are infected with dl6-95/β_2AR/Neo^{SV40} and treated with vehicle for 7 days. Group VI are infected dl6-95/β_2AR/Neo^{SV40} and treated with daily subcutaneous injections of 1 mg/kg dexamethasone for 7 days. Previously it has been shown that daily injections of 1 mg/kg dexamethasone result in an approximate doubling of lung β_2AR number in the rat.[87] After seven days, animals are challenged with ovalbumin. Animals are instrumented and the sensitivity to the β-agonist (-)-isoproterenol (as measured by decreased airway resistance) determined following exposure to methacholine. The results from this experiment determine the extent of inducibility of recombinant β_2AR expression and the effect on lung function as measured by changes in airway resistance following β-agonist treatment. Groups V and VI are included to distinguish between the anti-inflammatory properties of glucocorticoids versus their effects on increasing the expression of β_2AR gene driven by the inducible promoter. The effect of dexamethasone on the expression of the β_2AR gene whose expression is driven by the AAV P5 promoter, is evaluated. Therefore, an enhanced sensitivity to (-)-isoproterenol following methacholine administration provides a measurement of the effects of dexamethasone that are not directly due to enhanced transcription of the β_2AR transgene under control of the inducible promoter. Lungs from all experimental animals are removed and stored at -70°C for analysis by either *in situ* hybridization or immunohistochemistry determine the extent of recombinant β_2AR gene expression.

Effect of Exogenous Glucocorticoid Withdrawal on Lung Function

Sensitized Brown-Norway rats are divided into six groups with four rats in each group. Group I are infected with dl3-94/Neo^{SV40} and treated with the AAV vehicle for 14 days. Group II are infected with dl3-94/Neo^{SV40} and treated with dexamethasone for 14 days. Group III are infected with dl3-94/Neo^{SV40}, treated with dexamethasone for 7 days and then are withdrawn from glucocorticoids and treated with vehicle for an additional 7 days. Group IV are infected with dl3-94/β_2AR/Neo^{SV40} and treated with vehicle for 14 days. Group V are infected with dl3-94/β_2AR/Neo^{SV40} and treated with dexamethasone for 14 days. Group VI are infected with dl3-94/β_2AR/Neo^{SV40}, treated with dexamethasone for

7 days and then are withdrawn from glucocorticoids and treated with vehicle for an additional 7 days. Dexamethasone (1 mg/kg) or vehicle are administered via daily subcutaneous injections. After 14 days, animals are challenged with ovalbumin. Animals are instrumented and the sensitivity to the β-agonist (-)-isoproterenol (as measured by decreased airway resistance) determined following exposure to methacholine. The results from this experiment will determine the effect of exogenous glucocorticoid withdrawal on lung function as measured by changes in airway resistance following β-adrenergic agonist treatment. Lungs from all experimental animals are removed and stored at -70°C for analysis by either *in situ* hybridization or immunohistochemistry determine the extent of recombinant β_2AR gene expression.

Measurement of Airway Response

The procedure used to measure changes in airway resistance following methacholine challenge and subsequent treatment with β_2-adrenergic agonist is based on the original procedure for studying the mechanical properties of the lungs of guinea pigs.[3] This method has been adapted by many investigators to measure airway resistance in the rat lung.[37,139,149] Fourteen days after sensitization, rats are anesthetized with urethane (700 mg/kg intraperitoneally). The trachea is accessed via a midline incision and intubated with thin-walled stainless steel tubing (6 cm long). The intubation tubing is connected to a heated pneumotach (Hans Rudolph 8340, Kansas City, MO) and ports of the pneumotach are connected with latex tubing to differential pressure transducers (SCXL-EB, SenSym, Milpitas, CA). The instrumented rat is paralyzed (0.3 mg/kg gallamine) and the lungs are ventilated artificially (Harvard Apparatus Model 683, South Natick, MA). Heart rate is obtained by attaching surface electrodes to the skin that are connected to an ECG amplifer. Syringes (1 cc and 3 cc) are used to provide a volume calibration of the flow signal and a manometer is used to calibrate airway pressure. All physiological data are recorded on-line (Data Acquisition/Analysis, MP100 Acknowledge 3.0, BioPac Systems, Inc., Santa Barbara, CA). After completion of surgical procedures, animals are allowed to stabilize for 30 min. Methacholine is either infused into the jugular vein (1 mg/ml) or administered to the airways via a Marquest hand-held updraft nebulizer. The bronchodilatory effects of the β-adrenergic agonist (-)-isoproterenol are then evaluated after bronchoconstriction in

response to methacholine reaches a steady-state level. Isoproterenol is administered either via the jugular vein or the nebulizer.

Construction of a Glucocorticoid-inducible β_2AR transgene for introduction into Airway Epithelium by AAV

Alternative constructs that are useful in the present invention are constructs containing inducible promoters that allow the control of the expression of the β_2AR gene in the target cells in the body of the subject. The following experiments disclose the preparation of a recombinant AAV that includes the coding region of the β_2AR gene and whose expression in epithelial cells is controlled by glucocorticoids. The expression is evaluated in SPOC1 cells *in vitro*. The optimum expression levels of the β_2AR gene may be increased by the modification of the promoter and the glucocorticoid response element.

First, corticosteroids are frequently used to treat asthmatic patients. This is done principally to control the inflammatory component of asthma. Therefore, expression of the transgene can be controlled by a therapeutic agent that most asthmatic patients already use. Second, glucocorticoids increase the rate of transcription of several genes including the β_2AR.[5] This aspect of glucocorticoid action is considered in the design of the optimal β_2AR transgene for functional testing in airway epithelial cells *in vitro* and *in vivo*. Classically, glucocorticoids exert their effects by binding to a cytoplasmic glucocorticoid receptor causing the release of an associated 90 kDa heat shock protein and thereby allowing translocation of the receptor to the nucleus. Within the nucleus, glucocorticoid receptors form dimers that bind to DNA within steroid-responsive genes at consensus sequences called glucocorticoid response elements. This interaction changes the rate of transcription of the gene, most often resulting in induction of transcription, but in some cases gene expression can be repressed. The present inventors have identified the core GRE in the rat β_2AR gene as it functions in the HepG2 cell line as discussed below. Based on this work and other evidence, the expression of the rat β_2AR gene is induced by glucocorticoids. In these studies, the SPOC1 cell line is used to functionally characterize the *cis*-acting elements in the β_2AR gene that are involved in glucocorticoid induction. Glucocorticoid receptors bind to the consensus sequence GGTACAnnnTGTTCT (where n is any nucleotide). In some instances this may be a straight-forward interaction in which the receptor dimer bound to the GRE then interacts with basal transcription factors[67] or other DNA-binding

proteins[126,127] resulting in enhanced transcription of the target gene. However, in many cases the interactions are more complex. At composite GREs, the hormone receptor complex interacts with both specific DNA sequences and other transcription factors to regulate transcription of the target gene.[31,47,91] Some transcription factor binding elements that interact with glucocorticoid response elements include those for activating protein-1,[31] C/EBP[56] and hepatic nuclear factor 3 (HNF3).[148] Widely spaced glucocorticoid response elements have been shown to function in tandem to induce expression of the tryptophan oxygenase gene.[27] The data obtained from transient expression of β_2AR-luciferase fusion genes in HepG2 cells indicates complex regulation of β_2AR gene expression by glucocorticoids that appears to involve other as yet unidentified genetic elements.

Cloning of the Rat β_2AR Gene 5'-Flanking DNA

To study transcriptional regulation of β_2AR gene expression, a rat β_2AR genomic clone was inserted into the *Eco*RI site of λ phage Charon 4A from Dr. P. Buckland, University of Wales. The clone includes the 4190 bp section submitted to the Genebank/EMBL database,[16] plus an additional unsequenced section of aproximately 1400 bp in the 5'-flanking region. The portion sequenced by Buckland[16] includes 2251 bp of the 5'-flanking region, 1256 bp coding region, and 682 bp of the 3'-untranslated region. A 4200 bp section of the original clone was subcloned that encodes nucleotides -3912 to +322 (relative to the start of transcription) into the *Eco*RI-*Kpn*I sites of plasmid pGEM7zF(-) (Promega, Madison, WI). Independently, Jiang and Kunos[70] and McGraw *et al.*[88] discovered that a 2062 bp *Pst*I-*Pst*I fragment of the 5'-flanking region was entered incorrectly into the Genebank/EMBL database. The corrected sequence along with an additional ~1 kb of 5'-flanking sequence in the NCBI nucleotide sequence database under the accession number U35448. With reversal of orientation of the *Pst*I-*Pst*I fragment, the similarity between the 5'-flanking regions of the rat and human genes becomes 74%, as determined by the BESTFIT program of the GCG Sequence Analysis Software Package. This degree of identity is similar to the 73% reported between the human and mouse β_2AR genes.[39,95] Reversing the sequence conserves putative promoter elements that are found in the β_2AR genes of other species. A reverse complement CAAT box in the human and hamster genes is conserved in the rat, as are two TATA box-like sequences. From primer extension analysis, the start of transcription is –220[71] relative to the first nucleotide of the

initiator ATG for the receptor open reading frame. Figure 8A provides a schematic representation of the β_2-AR gene.

Computer analysis of the known sequence of the rat β_2AR receptor gene yielded seven potential glucocorticoid regulatory elements (Figure 8B). Six of the potential GREs are located upstream of the receptor open reading frame while the seventh GRE is located in the 3'-flanking region of the gene. Sequence comparisons were made between the seven putative β_2AR gene GREs and the distal GRE upstream of the mouse mammary tumor virus (MMTV) promoter.[103] The MMTV GRE, which contains the core GRE sequence TGTTCT, binds glucocorticoid receptor and is necessary for hormone responsiveness.[124] Studies show the putative GRE downstream of the receptor open reading frame was found to be nonfunctional. Attention was focused on the six GRE-like elements in the 5'-flanking region of the gene.

Transient Transfections of β_2AR Promoter Truncations

In order to determine whether the six putative GREs were functional, six β_2AR-luciferase fusion gene deletion mutants were generated. Among them, pβ_2AR(-3129/+126) and pβ_2AR(-2552/+126) contain all six putative GREs, pβ_2AR(-1115/+126) contains the proximal five putative GREs, pβ_2AR(-643/+126) contains GRE_5 and GRE_6, and pβ_2AR(-152/+126) and pβ_2AR(-62/+126) contain only the most proximal GRE. For experiments in which dexamethasone-stimulated promoter activity in different 5'-deletion constructs was tested, subconfluent cells in DMEM with 10% fetal bovine serum that had been stripped of steroids were transfected with 0.38 pmoles of the β_2AR-luciferase fusion genes, 2 μg pRSVβ-gal, 1 μg pRShGRα and pGEM-7Zf(-) to adjust the amount of total DNA per dish to 8.33 μg. To test the effect of dexamethasone on expression of the truncated β_2AR-luciferase fusion genes, HepG2 cells transfected with each of the six fusion genes were incubated with either vehicle or 0.1 μM dexamethasone for 8 hrs, and luciferase activity was determined. The HepG2 human liver cell line has previously been used to study glucocorticoid regulation of angiotensinogen gene expression.[13] HepG2 cells are deficient in functional glucocortocid receptors.[12] By this deficiency, the role of glucocorticoids in regulating β_2AR gene expression by cotransfection with pRShGRα, a glucocorticoid receptor-encoding expression plasmid, is investigated. The activity of pRSVβ-gal was used to correct for differences in transfection efficiency between individual experiments. Results from preliminary experiments indicated that 8 hours was the optimal time to observe

dexamethasone responsiveness since cell viability decreased with longer exposures to dexamethasone (data not shown). The data shown in Figure 9 depict the results of experiments in which progressively truncated β_2AR-luciferase fusion genes transiently transfected into HepG2 cells were tested for dexamethasone responsiveness. Approximate two-fold induction with 0.1 μM dexamethasone over that in the absence of added glucocorticoid was observed with pβ_2AR(-3129/+126), pβ_2AR(-2552/+126), and pβ_2AR(-1115/+126). This level of induction of luciferase expression is similar to the fold induction in β_2AR levels that has been observed in the lung following injection of glucocorticoids,[19,84,87] and with addition of glucocorticoids to cultured cells.[19,28,46,104,140,157] With pβ_2AR(-643/+126), the induction observed with 0.1 μM dexamethasone was approximately 1.5-fold. With pβ_2AR(-152/+126) and pβ_2AR(-62/+126), luciferase activity with the addition of 0.1 μM dexamethsone was not significantly increased over that in the absence of added glucocorticoid. As a positive control, N-600 prATLUC, a fusion gene containing a segment of the rat angiotensinogen gene with two functional GREs coupled to a luciferase-encoding gene, was used. In the presence of 0.1 μM dexamethasone, expression of N-600 prATLUC was increased approximately 8- to 10-fold, consistent with the level of induction by glucocorticoid previously demonstrated with this fusion gene.[13] Taken together, the data indicate that of the six putative glucocorticoid response elements in the 5'-flanking region of the β_2AR gene, only GRE_5 appears to be functional.

Truncation from the -2552 position to the -1115 position produced an increase in basal activity in the absence of added dexamethasone (Figure 9). This observed increase of basal activity in the shorter constructs is not unusual in studies of this type. One interpretation of this result is the presence of negative regulatory elements in the truncated region, in this case between -2552 and -1115. Alternatively, the difference in activity may also be related to the proximity of plasmid vector sequences to regulatory elements in the β_2AR gene sequence.

Transient Transfections Using a β_2-Adrenergic Receptor-Luciferase Fusion Gene with Mutated GRE_5

To test further the involvement of GRE_5 in glucocorticoid regulation of β_2AR expression, a plasmid pβ_2ARm1(-3129/+126) was constructed that had been mutated at position +6 of GRE_5 (GGGTGAGCTGTTCT → GGGTGAGCTATTCT). This mutation, the same

base change in oligonucleotide m1GRE$_5$ (Figure 10), is essential for glucocorticoid inducibility of a MMTV GRE.[103] The results demonstrate loss of glucocorticoid inducibility using pβ_2ARm1(-3129/+126) (Figure 11). Interestingly, in the absence of added dexamethasone, activity of pβ_2ARm1(-3129/+126) was markedly lower than that of pβ_2AR(-3129/+126) (Figure 11). It appears that basal expression of pβ_2AR(-3129/+126) in HepG2 cells that are over-expressing glucocorticoid receptor is relatively high despite removal of glucocorticoids from serum by charcoal stripping. Forty-eight hours prior to transfection, the HepG2 cells are switched to charcoal-stripped serum. Alternatively, GRE$_5$ contributes to basal activity of the β_2AR gene promoter.

Transient Transfections Using Putative GREs Fused to a Heterologous Promoter

To further examine the functionality of the putative glucocorticoid response elements, fragments containing either GRE$_1$, GRE$_5$, or GRE$_2$, GRE$_3$ and GRE$_4$ together were fused to pT81LUC, a luciferase expression plasmid driven by a minimal thymidine kinase promoter.[102] Sequences of the double stranded oligonucleotides containing GRE$_1$, GRE$_5$ and the MMTV GRE are shown in Figure 10. As a positive control, a MMTV-pT81LUC fusion gene was prepared which contains a previously demonstrated functional GRE.[17,80] An approximate 4-fold induction was observed with 0.1 μM dexamethasone using the MMTV-pT81LUC fusion gene (Figure 12). Activity of GRE$_5$-pT81LUC was induced 3.2-fold in the presence of 0.1 μM dexamethasone (Figure 12), a value that was higher than that observed with any of the β_2AR-luciferase fusion genes that included GRE$_5$. Activity of GRE$_1$-pT81LUC was not induced by 0.1 μM dexamethasone (Figure 12). Transfection of HepG2 cells with segment -831 to -708, which contains GRE$_2$, GRE$_3$, and GRE$_4$, fused to pT81LUC resulted in luciferase activity in either vehicle or 0.1 μM dexamethasone treated cells that was below that observed in mock-transfected cells. Of interest within this experiment, is the observation that GRE$_5$, when fused to pT81LUC and transiently transfected into HepG2 cells, resulted in 3.2-fold induction of activity. This level of fold-induction was similar to that obtained with MMTVsequence fused to pT81LUC. These results indicate either that the β_2AR promoter is a relatively weak substrate for GRE enhancer activity or that other segments of the β_2AR gene missing from our reporter gene constructs are necessary for full induction by glucocorticoids.

In Vitro Characterization of the Interactions of the Glucocorticoid Receptor and Other Putative Transcription Factors with β_2AR Gene DNA: Electrophoretic Mobility Shift Assays and Supershift Assays

Electrophoretic mobility shift assays and supershift assays are used to detect the presence of specific DNA binding proteins in SPOC1 cells treated with and without 0.1 μM dexamethasone. Sense and anti-sense oligonucleotides (~35-50 nucleotides) are commercially synthesized (Bio-Synthesis, Inc., Lewisville, TX). Complimentary oligonucleotides in equimolar amounts are heated to 100°C and cooled overnight to 25°C, aliquoted and stored at -20°C prior to use. Labeled probes are prepared by either end-labeling with [γ-^{32}P]ATP using T4 polynucleotide kinase or by filling in 5'-overhangs with a [α-^{32}P]dNTP using Klenow. Binding reactions are performed in a 20 μl volume that includes approximately 20,000 cpm labeled probe, 6 to 12 μg nuclear extract, 20 mM HEPES, pH 7.9, 60 mM KCl, 5 mM $MgCl_2$, 2 mM dithiothreitol, 10% glycerol, 200 ng polydI•dC (to reduce nonspecific binding), 1 μg bovine serum albumin, and unlabeled competitor oligonucleotides. After incubation for 30 minutes at room temperature, the reactions are loaded onto 6% non-denaturing polyacrylamide gels in 1x TBE (25 mM Tris, 25 mM boric acid, 0.5 mM EDTA) to separate protein-DNA complexes from free radiolabeled probe. Gels are dried and subjected to autoradiography. The electrophoretic mobility of DNA that specifically binds nuclear proteins are retarded compared to the mobility of DNA that is not complexed to protein. Observed DNA-protein complexes are characterized for specificity by competition with varying amounts of other DNA fragments; either unlabeled probe or other double-stranded oligonucleotides with similar sequences. In competition assays, increasing amounts of unlabeled double-stranded oligonucleotides that binds the transcription factor (*e.g.*, the glucocorticoid receptor) of interest competes with binding of labeled probe causing loss of binding signal as the concentration of the unlabeled probe is increased. Competition with a unlabeled double-stranded oligonucleotide with little sequence identity with the labeled probe will not change the intensity of the binding signal. To further delineate the proteins that bind to labeled probes, supershift assays are performed. For these studies, commercially obtained antibodies specific for the putative transcription factor (*e.g.*, glucocorticoid receptor, AP1, *etc.*) are added to the reaction mixture described above for either 16 hrs at 4°C or 50 min at 30°C prior to addition of the radiolabeled double-stranded oligonucleotide. When a putative transcription factor is

present in the DNA-protein complex, then the electrophoretic mobility of the complex are altered (usually retarded) due to binding of the antibody resulting in a "supershifted" profile. These results confirm the identity of the specific *trans*-acting factor(s) involved. For electrophoretic mobility shift assays and supershift assays, nuclear extracts are prepared from at least three different cell culture plates and at least three different experiments performed.

Electrophoretic Mobility Shift Assays Using Nuclear Extracts Prepared from Dexamethasone-Treated HepG2 Cells

Cells are cultured in the presence and absence of 0.1 μM dexamethasone for 8 hrs. Nuclear extracts from both groups of cells are prepared using the method of Andrews and Faller.[4] The protocol is a micro-preparation procedure that allows rapid extraction of DNA-binding proteins from small numbers of cells. Except where otherwise noted, centrifugations are done in an Eppendorf Model 5415C microfuge at maximum speed at room temperature. Approximately 10^6 to 10^7 SPOC1 cells from the control and dexamethasone treated groups are scraped into 1.5 ml ice-cold phosphate buffered saline, pH 7.4 and pelleted. Cells are re-suspended in 400 μl Buffer A (10 mM HEPES-KOH), pH 7.9, 1.5 mM $MgCl_2$, 10 mM KCl, 0.5 mM dithiothreitol, 0.2 mM phenylmethylsulfonylfluoride) at 4°C. Cells were allowed to swell for 10 min, then vortexed for 10 sec, centrifuged for 10 sec, and the supernatant discarded. The pellet is resuspended in 20 to 50 μl of Buffer C (20 mM HEPES-KOH, pH 7.9, 25% glycerol, 420 mM NaCl, 1.5 mM $MgCl_2$, 0.2 mM EDTA, 0.5 mM dithiothreitol, 0.2 mM phenylmethylsulfonylfluoride) at 4°C and incubated for 20 min. Cellular debris is removed by centrifugation for 2 min at 4°C and the supernatant containing DNA binding proteins is stored at -70°C. Nuclear extract protein concentrations are determined[11] using bovine serum albumin as the standard. The yield of this procedure is approximately 50-75 μg of protein per 10^6 cells, a sufficient quantity of nuclear protein for 10-12 lanes in a single electrophoretic mobility shift assay.

To determine if nuclear transcription factors could indeed bind to GRE_5 from the rat β_2AR gene, electrophoretic mobility shift assays were performed using as the probe a 35 bp double stranded oligonucleotide that includes GRE_5 and flanking sequence, and nuclear extracts prepared from HepG2 cells that had been treated with 0.1 μM dexamethasone for 8 hrs. In preliminary experiments in which increasing amounts of HepG2 cell nuclear extract

was added to radiolabeled GRE_5 probe, it was determined that 6 μg of nuclear extract resulted in optimum levels of shifted product (data not shown). The results of a representative experiment is shown which depicts an electrophoretic mobility shift assay in which the specificity of the interaction of HepG2 cell nuclear proteins with GRE_5 was assessed by competition analysis (Figure 13). Radiolabeled GRE_5 incubated with HepG2 cell nuclear extract resulted in a prominent shifted band (Figure 13). Addition of increasing concentrations of unlabeled GRE_5 displaced radiolabeled GRE_5 in a dose-dependent manner whereas the unlabeled oligonucleotide designated random oligonucleotide did not suppress radiolabeled GRE_5 binding (Figure 13).

Electrophoretic Mobility Shift Assays Using Recombinant Human Glucocorticoid Receptor

To further characterize the ability of GRE_5 to bind glucocorticoid receptor *in vitro*, we performed electrophoretic mobility shift assays with recombinant human glucocorticoid receptor and serial dilutions of various competitor oligonucleotides was performed. Radiolabeled GRE_5 incubated with recombinant human glucocorticoid receptor resulted in a single shifted band (Figure 14). Addition of increasing concentrations of unlabeled GRE_5 displaced radiolabeled GRE_5 in a dose-dependent manner (Figure 14). In contrast, increasing concentrations of either unlabeled GRE_1 or unlabeled $m1GRE_5$, with a single nucleotide change in the core sequence of GRE_5, did not compete with radiolabeled GRE_5 for binding to recombinant human glucocorticoid receptor (Figure 14). This change (G→A in position +6 of the GRE) had previously been shown to result in the complete loss of glucocorticoid inducibility of a MMTV GRE fused to a luciferase reporter gene.[103]

Transient Transfection Experiments to localize the segment of the β_2AR gene that contains essential elements for basal and glucocorticoid-stimulated expression

SPOC1 cells are cultured in monolayers as described above. Twenty-four hours prior to transfection, cells are split into 60 mm culture dishes containing 2 ml of growth media. Cell confluency are ~50% at the time of transfection. In a given experiment, cells are transfected using Lipofectamine (Gibco-BRL, Gaithersburg, MD) in triplicate with either pGL3-Basic (a negative control plasmid that has no promoter or enhancer sequences), or pGL3-Control (a positive control plasmid with promoter and enhancer activity driven by the SV40 viral promoter), or the β_2AR-Luciferase fusion genes. All cells are co-transfected with pRSVβ-gal (Promega, Madison, WI). pRSVβ-gal encodes β-galactosidase which is

used to adjust for transfection efficiency. Cells in 60 mm plates are co-transfected with 2.4 μg of DNA, which includes a particular β_2AR-Luciferase fusion gene (the amount of DNA transfected will depend upon the molecular weight of the construct), 0.4 μg pRSVβ-gal, and pGEM7Zf(-) as carrier DNA. Cells are then incubated overnight in growth media. After the incubation, fresh media are applied, and treatment cells are stimulated with 0.1 μM dexamethasone; control cells will receive the vehicle. Cells are incubated for an additional 8 hrs at which time cell lysates are harvested using Lysis Buffer (Promega, Madison, WI). Cell lysates are assayed for luciferase activity using the ProMega luciferase assay system (Madison, WI) and β-galactosidase using the Galacto-Light system (TROPIX, Bedford, MA) using a Monolight Model 2010 Luminometer. To adjust for transfection efficiency, firefly luciferase activity are normalized to β-galactosidase activity. Firefly luciferase activity, corrected for β-galactosidase activity, for each construct are compared to values obtained with pGL3-Control, a luciferase reporter gene driven by the SV40 promoter (a positive control which should give high firefly luciferase activity in transfected cells) and pGL3-Basic (a control lacking a promoter which should result in low firefly luciferase activity in transfected cells). These experiments identify the minimal promoter that directs β_2AR gene expression in SPOC1 cells, the glucocorticoid responsive element and other enhancer-like and/or repressor-like mechanisms that regulate β_2AR gene expression. Within each experiment, constructs are tested in triplicate and each experiment is repeated four to five times.

In Vitro Characterization of the Interactions of the Glucocorticoid Receptor and Other Putative Transcription Factors with β_2AR Gene DNA: DNase I Footprinting

In order to establish the identities of the factors interacting *in vivo* to glucocorticoid responsiveness to the β_2AR gene, a comparative analysis of the *in vitro* footprints obtained with DNase I are performed. These experiments are conducted in order to detect possible transcription factor interaction with β_2AR gene DNA. DNase I footprinting are performed using previously described methods.[50] Nuclear extracts are prepared from untreated and 0.1 μM dexamethasone-treated SPOC1 cells as described for electrophoretic mobility shift assays. Target DNA (either restriction fragments < 120 bp or complementary oligonucleotides) that includes the GRE and possible interacting cis-elements are either end-labeled with [γ-^{32}P]ATP using T4 polynucleotide kinase or by filling in 5'-overhangs with a

[α-^{32}P]dNTP using Klenow. Labeled DNA fragments are incubated with nuclear extracts prepared from untreated and dexamethasone-treated SPOC1 cells in a binding buffer (10 mM Tris-HCl, pH 7.5, 50 mM NaCl, 0.05% Nonidet P-40, 1 mM EDTA, 1 mM DTT and 10% glycerol) for 30 min at room temperature. The reaction mixture are digested with DNase I. Digestion is stopped with a solution containing 30 mM EDTA and 0.15% SDS. Exact conditions (amount of nuclear extract, DNase I concentration, digestion time, *etc.*) are optimized. Following phenol-chloroform extraction, pellets are denatured and resolved on 6% polyacrylamide-urea sequencing gels. Protected regions are visualized by autoradiography to allow identification of specific bases involved in transcription factor binding. Identification of the specific nucleotide sequences involved allows the determination if more than one region of the gene is involved in transcription factor binding. For both untreated and dexamethasone-treated cells, nuclear extracts are prepared from at least three different cell culture plates and used in DNase I footprinting analysis.

Deletions and Mutagenesis

In order to confirm the functional significance of the identified *cis*-elements involved in glucocorticoid regulation of β_2AR gene expression, mutations are introduced into putative regulatory sequences using the method of Landt *et al.*[77] Although changing sequence can change secondary structure which can in turn produce an effect, mutagenesis is a standard and time tested method for determining the role of potential elements in transcriptional and other genetic events. Only short sequences are changed which should minimize effects on secondary structure. Mutagenic fragments are created with a two-step PCR procedure that includes an intermediate purification step. In the first PCR step, a 5'-universal primer and a 3'-mutagenic primer are used to generate a double-stranded mutated fragment. The PCR products are separated from the primers on 1% agarose gels, and the fragments of interest are eluted. In the second PCR step, the purified product from the first PCR reaction is used as the 5'-mutagenic primer in combination with a second 3'-universal primer to generate the final product. The product of the second PCR step is then digested with appropriate restriction endonucleases and is subcloned into an appropriate plasmid vector. Primer design and PCR conditions are determined for the sequence to be mutagenized. However, the 3'- and 5'-universal primers will incorporate restriction sites that facilitate rapid subcloning of mutagenized fragments. Sequences are verified using the dideoxynucleotide chain termination method[123] and Sequenase (United States Biochemical

Co., Cleveland, OH). Functional capabilities of the mutagenized fragments are determined in transiently transfected SPOC1 cells treated with 0.1 μM dexamethasone and with electrophoretic mobility shift assays with nuclear extracts prepared from dexamethasone-treated SPOC1 cells as described above.

Identification of Functional β_2AR Coupled to Adenylyl Cyclase in the Rat Tracheal Epithelial Cell Line SPOC1

Cell Culture: Tracheal Epithelial Cell Line SPOC1

SPOC1 cells are a continuous cell line spontaneously derived from secondary rat tracheal epithelial cultures.[32] They are nontumorigenic in nude mice, maintain a diploid karyotype, and when implanted into denuded rat tracheas form a stratified squamous epithelium that eventually forms glandlike invaginations into the surrounding lamina propria.[32] The SPOC1 cells utilized in these experiments were originally provided by Dr. Patrice Ferriola (Chemical Industry Institute of Toxicology, Research Triangle Park, NC). SPOC1 cells are grown in Dulbecco's Modified Eagles Medium (DMEM) and Ham's F-12 Medium (1:1) supplemented with 5% fetal bovine serum, 0.1 μg/ml hydrocortisone, 5 μg/ml insulin, 100 U/ml penicillin G and 100 μg/ml streptomycin as previously described.[32] In experiments in which the effect of dexamethasone is tested on the expression of β_2AR and coupling to adenylyl cyclase, hydrocortisone is removed from the media 72 hrs prior to the experiment.

SPOC1 cells are useful to determine the β_2AR function in lung epithelium under defined conditions. In preliminary experiments, β_2AR numbers are determined by radioligand assays using [^{125}I]cyanoiodopindolol ([^{125}I]CYP). [^{125}I]CYP binding to SPOC1 cell membranes was to a single, saturable site that displayed high affinity as demonstrated in the representative Scatchard plot (Figure 15). From this experiment, the [^{125}I]CYP dissociation constant was 10 pM and the binding site concentration was 60 fmol/mg protein. From competition experiments with [^{125}I]CYP, the rank order of potency of adrenergic agonists was isoproterenol (K_i=0.07 ± 0.04 μM) < epinephrine (K_i=0.5 ± 0.2 μM) < norepinephrine (K_i=11 ± 5 μM) (data not shown). Thus, the [^{125}I]CYP the binding site has pharmacological characteristics of the β_2AR subtype. To determine whether the β_2AR in SPOC1 cells is functionally coupled through $G_s\alpha$ to adenylyl cyclase, cyclic AMP accumulation was measured in cells treated with isoproterenol, a β-adrenergic agonist.

Preliminary experiments were conducted in order to determine the effect of the phosphodiesterase inhibitor isobutylmethylxanthine (IBMX) on isoproterenol-stimulated cyclic AMP accumulation (Figure 16). Cyclic AMP production in control (vehicle-treated) cells was 0.27 ± 0.08 fmol/min/mg protein. The addition of 100 μM IBMX resulted in a small, but statistically insignificant increase in cyclic AMP accumulation to 0.40 ± 0.04 fmol/min/mg protein. In the presence of 10 μM isoproterenol, cyclic AMP production was significantly ($p < .05$) increased over that of control cells to 3.17 ± 0.57 fmol/min/mg protein. Cyclic AMP production was further increased to 5.95 ± 1.4 fmol/min/mg protein in the presence of both 100 μM IBMX and 10 μM isoproterenol. The results of these experiments demonstrate that SPOC1 cells express the β_2AR subtype and that the receptor is functionally coupled to adenylyl cyclase and generation of intracellular cyclic AMP. Airway epithelial cells in a number of mammalian species have been shown to express the β_2AR subtype.[30,72,101,125] Therefore, SPOC1 cells have retained an important signal transduction pathway in the regulation of lung epithelial cell biology.

Transient Transfections of SPOC1 Cells

Preliminary experiments show the optimum methodology for transiently transfecting SPOC1 cells. Calcium phosphate co-precipitation and a cationic liposome-mediated method are compared. Lipofectamine (Gibco-BRL, Gaithersburg, MD) was consistently superior to calcium phosphate co-precipitation for SPOC1 cell transfections as judged by expression levels of pβ_2AR(-3129/+126) (data not shown). Cells were transiently transfected with a total of 2 μg of DNA which includes pβ_2AR(-3129/+126), a positive control plasmid pRVL-SV40 that expresses *Renilla* luciferase under the direction of the SV40 viral promoter, and pGEM 7Zf(-) DNA. *Renilla* luciferase activity was used to correct for differences in transfection efficiencies between individual experiments. Luciferase activity is measured in cell lysates using the Dual Luciferase Assay Kit (Promega, Madison, WI), which allows measurement of Firefly and *Renilla* luciferase activity in rapid succession in a single tube. Firefly luciferase activity, which arises from pβ_2AR(-3129/+126), corrected for *Renilla* luciferase activity was linear in SPOC1 cells transfected with increasing amounts of pβ_2AR(-3129/+126) (data not shown). In preliminary experiments, the effect of dexamethasone on expression of pβ_2AR(-3129/+126) in SPOC1 cells is tested. Dexamethasone was added for 8 hrs prior to harvesting cell lysates for determination of

luciferase activity. Similar to results obtained with HepG2 cells, 0.1 μM dexamethasone produced an approximate 2-fold induction in luciferase activity in transiently transfected SPOC1 cells (Figure 17). There was no induction of luciferase activity by dexamethasone in cells that had been transiently transfected with $p\beta_2AR(-62/+126)$. These results indicate that the SPOC1 cell line is a suitable model for studying transcriptional regulation of β_2AR gene expression by glucocorticoids and for testing expression and regulation of β_2AR transgenes carried in recombinant viruses.

Reference is made to a number of publications and patents in the present application. There mentioned documents are incorporated in their entirety by reference.

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